ERRATA

Page No.	Line No.	Correction
1	6 from the bottom	spelling: Feira
5	Figure 1	Kafulafuta River is the river on the north of Kadola area and Lukanga River is the river to the South
8	17	spelling: Oftendahl
26	2	formula should read: $M = \sum_{N}^{i=1} \frac{X_i}{N}$
33	7	spelling: Livingstone
33	Figure 3	Feira should be marked in the extreme south east corner of field area
46	Figure 6	Mulungushi River should be marked on the river in the extreme south east corner of field area
47	6 from the bottom	spelling: Mulungushi
56	14	spelling: grained
90	6 from the bottom	should read: Q - mode method utilises the correlations between the samples
95	9	N = n
103	Table 9	Footnote to be added: The reliability of these mean values depends on the elements. See text
104	Table 10	As for Table 9
104	Table 10	Mkushi South = Mtuga South Mkushi North = Mtuga North
120	6	0.7 = 0.66 0.6 = 0.56
278	4	spelling: media = medium

A

THESIS

entitled

PROVINCIAL AND REGIONAL GEOCHEMICAL STUDIES IN ZAMBIA

submitted for the
degree of

DOCTOR OF PHILOSOPHY
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By
ASHLYN ARMOUR-BROWN

Royal School of Mines,
Imperial College

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ABSTRACT

The location and definition of the boundaries of metallogenic provinces and/or districts is usually only accomplished after successful mining and/or mineral exploration has defined the limits of the occurrences of the type of mineralisation in question. Some research in the past has been directed at locating metallogenic provinces by geochemical methods. They have met with some limited success. The main limitation to geochemical methods has been the difficulty of collecting and analysing an adequate number of representative rock samples in order to define the areal extent of a metallogenic province. Drainage sediment sampling overcomes the first and to some extent the second of these problems.

This study was designed to investigate the viability of low density drainage sediment sampling as a method for identifying metallogenic provinces from the regional background variations. Drainage sediment samples collected at a density of one sample every 75 sq. mi. over 80,000 sq. mi. of central Zambia were analysed for up to 16 elements. A two dimensional moving average technique was employed to smooth the data so that overall minor-element trends could be defined more clearly. The results of this study confirmed low density drainage sediment sampling as a method for identifying copper and tin metallogenic provinces in conditions similar to those in Zambia. Subsequent rock sample data showed that the enhanced tin background in the drainage sediment in the tin metallogenic district was a reflection of increased tin levels in the bedrock. The rock sample data from the copper provinces was equivocal, and it was concluded that the enhanced copper background in the drainage sediment in these areas was due either to an increased background in the bedrock or increased occurrences of minor mineralisation.

It was recognised that the distributions of many of the elements reflected known geological and secondary features. It was, however, extremely difficult to interpret the controlling features from the single element distributions. The same problem is encountered in the interpretation of multi-element data from reconnaissance (high density drainage sediment sampling) geochemical studies. R-mode factor analysis was evaluated, therefore, as a method of extracting minor-element associations, from which the various geologic and secondary environmental controlling features might be interpreted. A system of R-score measurements was evaluated as a method of delineating the geographical distribution of the controlling features as they are defined by the minor-element associations. R-mode factor analysis was carried out on the provincial data (low density sampling), and regional data from two areas of 2000 sq. mi. each sampled at a density of 1 sample every 4 sq. mi. and 1 sample every 2 sq. mi.

This study confirmed that R-mode factor analysis extracted the overall minor-element associations which could be related to the main controlling features, and that the R-scores of the samples correctly delineated the distribution of the controlling features. Subsequent rock and soil sampling showed that the minor-element associations extracted from the drainage sediment data were more similar to those from the rocks, than were those from the soil data, and that the R-score distributions correctly indicated bedrock types where they were not previously known to occur.

It is suggested on the basis of this work that broad scale drainage sediment sampling be carried out over other areas where the geology and/or provincial geochemistry is largely unknown, to obtain a broad evaluation of the geology and possible metallogenic provinces and districts, in order to delineate smaller areas for detailed mineral exploration.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND AND AIMS OF RESEARCH

1.1.1 Wide interval geochemical stream sediment sampling for locating metallogenic provinces

Geochemical stream sediment sampling methods have been extensively used for the location of individual mineral deposits by sampling drainages at relatively close intervals such as one sample every square mile. Wide interval stream sediment sampling (1 sample every 50-100 square miles) carried out over 15,000 square miles of the Basement Complex in Sierra Leone, has shown that this sampling method also brings out variations of geochemical background, and in particular, it demonstrated that there was a significant increase in chromium background on a regional scale associated with an area of known chromium mineralisation (Garrett, 1966).

Detailed geochemical drainage reconnaissance in small areas in different parts of Zambia indicated that there are variations in background between the areas, occurring over all the geologic units. These appear to be related to the metallogenic provinces in which some of the areas are situated. For example, an area in the Copperbelt has comparatively high copper background in stream sediments associated with all rock types, although mineralisation is largely restricted to a single formation. In the Fiera carbonatite area too, there is a general high background of strontium, niobium and vanadium compared to areas of similar geology elsewhere (Webb et al, 1964).

The occurrence of relatively well defined metallogenic provinces in Zambia, and the existence of background variations associated with them, suggested that Zambia would be a fruitful area for the assessment of the use of wide interval stream sediment sampling as a means of defining metallogenic provinces. Such a method for elucidating metallogenic provinces would greatly aid mineral exploration in the initial stages by directing attention to those areas where more conventional reconnaissance methods required to locate specific deposits can be concentrated.

1.1.2 Regional geochemical stream sediment reconnaissance and the interpretation of multi-element data by statistical and mathematical techniques

Stream sediment reconnaissance samples have until recently been analysed only for the few elements of specific economic interest. Variations in the background levels of these elements related to bedrock geology (Hawkes et al, 1956) suggested to Webb (1958) the use of multi-element analyses in order to gain more information and better interpretation of the bedrock geology, in order to aid in the evaluation of anomalous metal values in terms of mineralisation.

Regional stream sediment reconnaissance has been carried out over several 1000-3000 square mile areas, and analysed for up to 22 elements in Zambia, Sierra Leone and the United Kingdom. The interpretation of the geochemical data from these areas by conventional methods have shown some of the relationships between the various minor element patterns of the stream sediments and the primary and secondary features of the environment. For example, in the Namwala Concession area in Zambia the analytical data of 10 elements from about 4000 samples over a 3000 square mile area of Pre-Cambrian Basement and Katangan rocks were plotted and evaluated. The following conclusions were drawn (Webb et al, 1964).

(a) patterns of background variation of Co, Cu, Cr, Mn, Ni, Pb, Ti, V and Zn were related to the major geologic units,

(b) abnormally high copper background values were associated with areas of known copper mineralisation, and

(c) variations in minor element background values were also related to topography but only in so far as the latter is related to the geology (Webb et al, 1964).

The interpretation, however, of a large quantity of geochemical stream sediment data in terms of the features controlling the element distributions is extremely difficult because of the large variance of the results due to the combined sampling and analytical errors, and the mixing, in the streams, of sediments from different sources.

Computerised data handling techniques, and statistical and mathematical interpretational techniques such as two dimensional moving-average, trend surface, and factor analysis were used for aiding in the interpretation of regional geochemical data from Sierra Leone (Garrett, 1966), and demonstrated their ability to elucidate minor element variations. In particular, moving average and trend surface analysis were found to smooth the data, which made contouring easier and brought out regional background variations less easily detected by visual inspection of the untreated data. Factor analysis of the multi-element data, on the other hand, explained the variations of the elements in terms of three components, which corresponded to streams draining granite, metal poor granite facies and ultrabasic rocks. These results indicated the potential of factor analysis in recognising the underlying features controlling the variations within a set of complex numerical data.

Large areas of Zambia have been sampled by geochemical reconnaissance methods and geologically mapped by the mining companies during their mineral exploration programmes. The vast amount of geochemical data, however, have not been easy to interpret meaningfully in terms of the controlling features such as the complex bedrock geology which occurs in Central Zambia, mineralisation and secondary environment. These interpretational problems and the availability of regional geochemical reconnaissance samples suggested that it would be fruitful to evaluate the use of factor analysis of multi-element data as an aid in classifying the source of stream sediment samples.

1.1.3 Aims of research

The aims of this research are, therefore, to determine:

(a) the validity of wide interval stream sediment sampling as a means of defining metallogenic provinces in conditions of mixed bedrock geology, mineralisation, and secondary environment as they occur over 80,000 sq. miles of Precambrian Basement and Katangan rocks in central Zambia, and to determine:

(b) the role of statistical and mathematical procedures in obtaining an improved interpretation of multi-element data from regional reconnaissance drainage sediment samples in terms of bedrock geology, mineralisation and secondary environment. The latter aspect of the study was also carried out on samples from two 2000 square mile areas in Zambia.

1.2 LOCATION OF FIELD AREAS

Wide interval stream sediment sampling, referred to from now on as 'provincial geochemical reconnaissance' was carried out between the Congo in the north, the Zambezi river in the south and longitudes 26°E and 30°E. This area will be referred to in the thesis as central Zambia (Fig. 1). This area was chosen because:

(a) it includes most of the better known metallogenic provinces in Zambia,

(b) the geology is relatively well known and generally considered favourable for mineralisation, and

(c) access is reasonably good allowing for a relatively even sample distribution.

The areas where more detailed drainage reconnaissance were carried out, from now on referred to as 'regional geochemical reconnaissance', include 2000 square miles of the Kadola and Lusaka East mineral concession areas held by Roan Selection Trust and Chartered Exploration, respectively. These areas were chosen (a) because the geology is relatively well known, (b) because the mineral potential is considered good, and (c) because the drainage sediment samples taken during the routine mineral exploration by the respective companies were available.

The Kadola area is bounded by the Kafue River to the west and north west, the Kafulafuta River to the north, the Lukanga River to the south and the main Copperbelt-Broken Hill* road to the east (Fig. 1).

The Lusaka East area is bounded by the Chongwe River on the west, longitude 29° 45' on the east, and latitudes 15°00' and 15°30' on the north and south, respectively.

1.3 LAYOUT OF THESIS

The layout of this thesis falls into four main sections as follows:

(a) the first section, chapters 1 and 2, contains background information. It provides an introduction which deals with the aims and location of the field areas in the first chapter and with previous research in the second chapter;

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*The town of Broken Hill has been renamed Kabwe by the Zambian Government since 1969, but will be referred to as Broken Hill throughout this thesis.

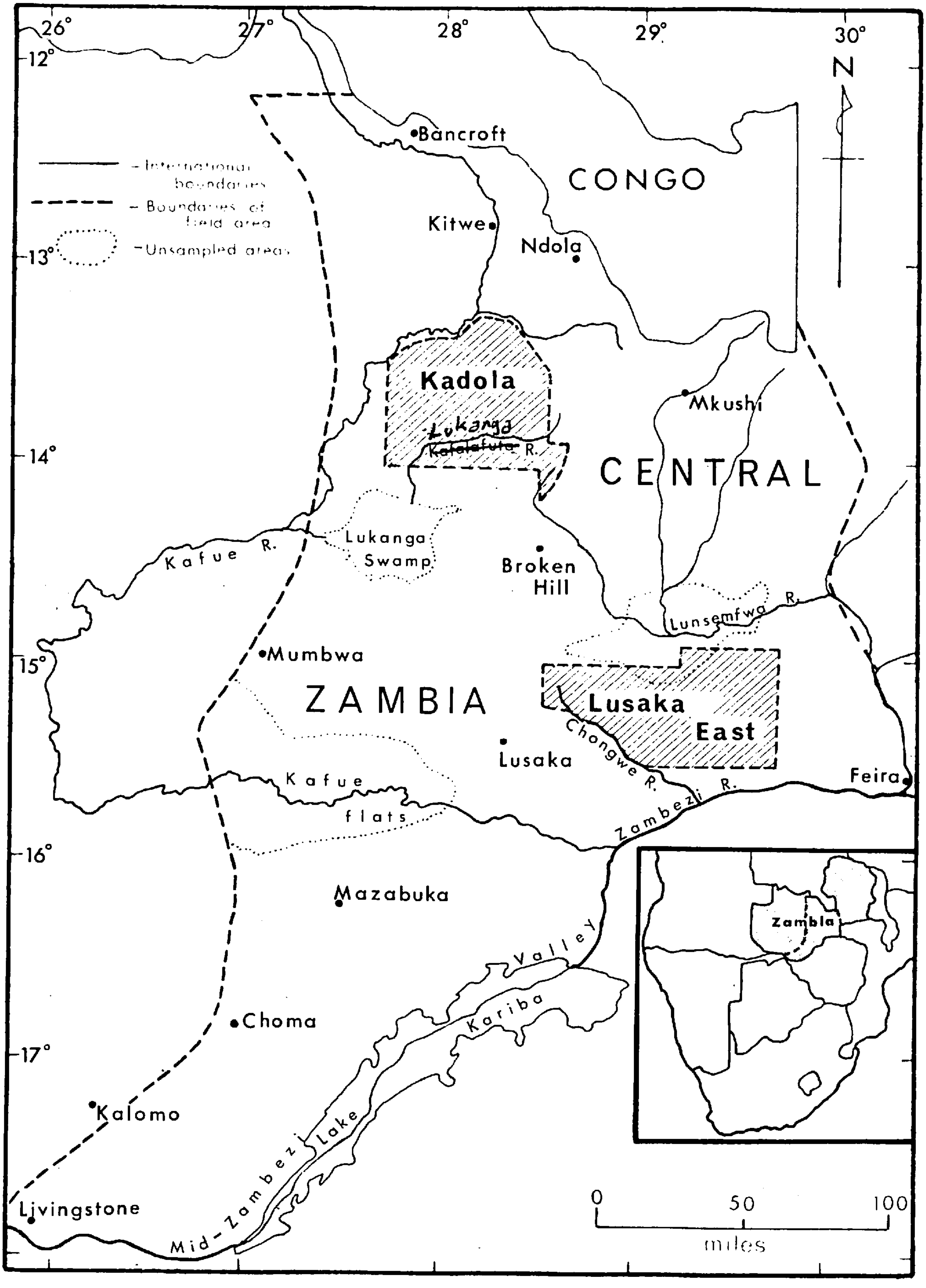

Fig: 1 Location of field areas.

(b) the second section, chapters 3 and 4, incorporates a description of the field areas in chapter 3, and field sampling, analytical, data handling and statistical methods used, in chapter 4;

(c) the third section, chapters 5 and 6, is largely descriptive, dealing with the results of the provincial reconnaissance in chapter 5, and with the regional reconnaissance in chapter 6;

(d) the fourth section, chapters 7 and 8, contains the interpretation and conclusion of the results, with the discussion of results in chapter 7, and with conclusions and suggested future work in chapter 8.

CHAPTER 2

GENERAL GEOCHEMICAL BACKGROUND TO RESEARCH AND PREVIOUS WORK

2.1. GENERAL GEOCHEMICAL BACKGROUND

2.1.1. Metallogenic provinces and their detection by geochemical methods

In 1913, De Launay proposed the term 'metallogenic province' to describe areas where certain kinds of mineral deposit preferentially occur, and since then it has been generally accepted as a working definition. Because of the lack of any exact criteria, a metallogenic province has not been defined in any greater detail than by Turneaure (1955), who uses the term ....'in a broad sense to refer to strongly mineralised areas or regions containing ore deposits of a specific type or groups of deposits that possess features suggesting a genetic relationship'. Implied, although unstated in this definition, is the concept of the size of a metallogenic province, which was suggested as extending at least 1000 km in one direction by Petrachek (1965). Smaller well outlined regions, which are considered mining districts, because of the same type of mineral deposits Petrachek defined as 'metallogenic districts'. These terms will be used in this thesis as they have been defined in these rationalisations.

The hypothesis that metal values are substantially increased, in rocks within a metallogenic province, in those metals forming the ore deposits has been shown to be true in some cases. Tin was found to be enhanced by 5 to 125 times the clark in granitic rocks genetically associated with the tin deposits of Malaya, Laos and Haut Tonkin (Goloubinoff, 1937). Goloubinoff also demonstrated that the concentration of gold was 8-25 times the clark in igneous rocks in gold bearing regions in Haut Tonkin, Congo and Guinea. High concentrations of other elements in various rock types have also been found to be a useful guide to mineral deposits of the same or associated elements in Russia (Kreiter, 1968).

In the Basin and Range area of Arizona a number of attempts have been made to relate minor element content in the minerals of the acid igneous rocks in the area to the metallogenic deposits present. For example, the lead content in potash feldspars of quartz monzonite intrusions were found to be enhanced in areas of major lead production (Slawson and Nackowski, 1959). Copper was found to be enhanced in the biotites of quartz monzonite intrusions associated with major copper deposits. Lead and zinc contents in biotites, however, have more complex relationships with mineral deposits which were thought to be due to the hydrothermal alteration of the sampled acid igneous rocks (Parry and Nackowski, 1963). The lead content in orthoclase in the granitic rocks around Oslo, was also found to have a complex relationship with associated lead mineralisation (Oftendahl, 1954). Oftedahl concluded from his work that it was almost impossible to incorporate lead into orthoclase at certain high temperatures, whereas low temperature orthoclase such as microcline could incorporate considerable quantities of lead. This feature resulted in a negative anomaly for lead in orthoclase of a granite associated with lead mineralisation. Putman and Burnham (1963) carried out sampling traverses over acid igneous rocks in Northwestern and Central Arizona and analysed the ferromagnesian phase, mostly biotite, for a number of elements in an attempt to define metallogenic provinces. They showed that the known areas of copper mineralisation were reflected by anomalously high copper in the samples from associated plutonic bodies. They concluded, however, that in order to detect and define regional trends, two-dimensional sampling must be carried out on a large scale because of the apparent random nature of the variation of element content that occurs within a plutonic unit, as well as between units.

These attempts at defining and detecting metallogenic provinces by sampling acid plutonic rocks have two main limitations for general use in mineral exploration. Firstly, they neglect types of mineralisation which are not genetically associated with acid plutonic rocks such as stratiform copper deposits in sedimentary rocks; and secondly they indicate that single rock samples give a poor minor element representation for a rock unit as a whole. This suggests that a large number of rock samples must be taken and analysed before a realistic picture of the geochemistry is obtained. Rock sampling on an adequate scale would be difficult in most areas and impossible in many where overburden covers all but the most competent, and therefore often unrepresentative, units. A condition which is usually encountered in a tropical environment.

2.2. GEOCHEMICAL STREAM SEDIMENT RECONNAISSANCE

2.2.1. Stream sediment analyses as a measure of the primary geochemistry

In 1954-55 Hawkes, Bloom, Riddell and Webb (1956) covered some 27,000 miles of New Brunswick analysing the stream sediments, using cold-extractable methods for measuring the heavy mineral content. Not only did this method locate specific drainages coming from possible economic mineral deposits, but it also outlined broad scale patterns related to major geologic units. This latter observation suggested the possibility of regional geochemical maps based on multi-element analysis of stream sediment samples defining minor element relief, which might aid in geological interpretation and indicate areas of increased mineral potential (Webb, 1958).

Since then a number of regional geochemical reconnaissance surveys using drainage samples have been made, in both temperate and tropical climatic areas in addition to the work in Zambia already referred to in Chapter 1 (Webb et al, 1964).

For example in Sierra Leone, Viewing (1963) and James (1965) sampled over 1000 square miles of mineralised schist belt in the plateau terrain of the Sula Mountains - Kangari Hills area underlain by Pre-Cambrian Kambui schists and surrounded by synkinematic granite. The streams which are incised through largely alluvial and colluvial sediment, were sampled on the basis of 4-5 samples per square mile. The minus 80-mesh fraction of these samples was selected for analysis after tests showed that this fraction gave good contrasts and the most uniform concentrations for the analyses of the same sample. Spectrochemical methods were used in analyses for up to 22 elements. The results for 11 of these elements were presented on separate maps.

These investigations demonstrated:

(a) that the sampling density could have been halved without any significant loss of detail,

(b) that the distribution of the mafic elements tended to be higher in the schist belts,

(c) that the higher standard deviation ranges of the elements in the schist belts reflect the greater local variation in lithology than in the geologically more uniform areas elsewhere,

(d) that lead is higher in the surrounding granite areas,

(e) that higher arsenic values were in some cases related to gold mineralisation,

(f) that higher molybdenum values indicated molybdenum mineralisation related to tectonic features, but enhanced values in some areas were related to duricrusted soil overlying basic and ultrabasic rocks,

(g) that duricrusted latosols with nodules of manganese and iron hydroxides were responsible for considerable concentrations of other minor elements particularly cobalt,

(h) that the spectrographic analytical technique with a precision of ±40% at the 95% confidence level was adequate to bring out significant variations for most of the elements.

Geochemical studies over similar schist belts including some 480 square miles of the Gori, Kambui, and Nimini Hills area of Sierra Leone gave very similar results (Garrett, 1966). These results combined with those from the other schist belts in Sierra Leone indicated that background variations of some of the minor elements between the schist belts could be related to known metallogenic districts, petrographic provinces and secondary environment. For example:

(a) arsenic values increased in areas of known gold mineralisation,

(b) higher chromium levels reflected areas of chromite occurrence,

(c) several molybdenum anomalies occurred in areas of known molybenite mineralisation, and

(d) tin anomalies were related to aplitic dykes which were thought to be a source of some placer tin deposits.

Overall geochemical data relief was greatest in the Kambui area compared to the other areas. This was thought to reflect the increased geologic complexity in Kambui schist belt as opposed to the relative simplicity of the other areas. Chromium and nickel were highest in the ultrabasic rocks of the Kambui, Nimini compared to the other areas, and copper was highest in ultrabasics of Kambui, Nimini and highest in the basic rocks of the Sula Mountains and Kangari hills. Garrett suggested that these differences were due to differences of petrographic province of the ultrabasic intrusives. Lead values in granites tended to be highest over the Kangari hills where there is thought to be later metasomatic granites than elsewhere. The duricrusted soil type was found to be the most important secondary environmental feature affecting the minor element distribution in the stream sediments. Lead values were enhanced in all duricrusted areas. Cobalt, chromium, copper, manganese, nickel and vanadium are enhanced and depleted to a different extent in the duricusted soils in the various areas. Garrett suggested that these differences are due to the manner in which the elements are held in the bedrock. For example, an element held in a silicate mineral will behave differently in the secondary environment than one held in a resistate mineral.

In addition to these relatively detailed geochemical reconnaissance surveys, Garrett sampled stream sediments, soils and rocks over 15,000 square miles of the Basement Complex at a density of one sample every 50-100 square miles. The existence of high chromium background values in areas of known chromite mineralisation has already been mentioned in the introduction. Other features revealed by this survey include a general northeast-southwest trending trough of low values of mafic elements with high values towards the northwest and southeast. This feature is considered to reflect differences in the geochemistry of the rocks prior to granitisation. A comparison of results from the different sample media showed a fair correspondence indicating that bedrock is the dominant feature controlling most of the minor element distributions in the drainage sediments.

Regional geochemical reconnaissance surveys have also been carried out over three areas of 1000 square miles each in Devonshire, Derbyshire and Denbighshire in the United Kingdom. In general, the broad features of background variations of most of the minor elements analysed, correlate with the major geological units which outcrop in these areas. Mineralisation, contamination from smelters and previous mining activity, secondary environmental features and glacial drift also controlled the minor element variations in the stream sediments.

For example in Devonshire, stream sediments: (a) draining the Dartmoor granite have enhanced Pb, Sn and lower Co, Cr, Cu, Ni, Ti and V compared to the surrounding sediments, and in addition an As, Sn metasomatic aureole extending further than the known thermal aureole was noted to occur around the granite, and (b) draining diabase intrusions had enhanced Cr, Ni and Ti. In Denbighshire stream sediments: (a) draining Ordovician felsite intrusions had low Cr, Ni and V, and (b) draining Lower Palaeozoic sediments had higher Cr, Ti, V, and to a lesser extent Co, Cu, Mn, Ni and Zn, compared to later sediments. In Derbyshire stream sediments draining argillaceous bedrock had higher Cr, Cu, Ni, Ti and to a lesser extent Co, Fe, Mn and Pb compared to those draining other rock types. Stream sediments draining black marine shale facies in all areas had particularly high molybdenum. In Devonshire this enhanced molybdenum was associated with selenium and in Denbighshire with arsenic and Derbyshire with arsenic and selenium (Fletcher, 1968). Stream sediments draining mineralisation had anomalous metal values. In particular, tin anomalies are associated with the tin mineralisation associated with the Dartmoor granite. In all three areas Pb, Zn and Cu anomalies are associated with mineralisation in these metals. Some of these Pb, Zn and to a lesser extent Cu anomalies, and Ba anomalies in Derbyshire, were,however, clearly due to contamination from smelters and previous mining activity. Criteria were developed by Taylor (1968) to differentiate between anomalous samples due to smelting contamination and those due to mineralisation. The mobile elements in the secondary environments, which include As, Co, Fe, Mn, Ni and Zn, were found to be enriched in the moorland areas of Denbighshire, Devonshire and to a lesser extent in Derbyshire. This latter feature was found to be due to the solution of manganese and iron in the acid groundwater of the peaty, poorly drained moorland soils, and their subsequent precipitation in the stream channels. The acid groundwater holds these elements in solution until entering a stream channel where the pH, Eh and evaporation increases resulting:(a) in the oxidation of first iron followed by manganese from the bi-valent to tetra-valent states, and (b) their precipitation and concentration in the drainage channels as concretions or coatings on particles. The other elements held in solution in the acid groundwater are scavenged by these oxidates and are therefore enriched in the moorland stream sediments with manganese and iron (Horsnail, 1968).

Horsnail showed that drainages in which this manganese precipitation was taking place had a reducible to total manganese ratio five times greater than that in streams draining freely drained soils; the reverse was found to be true for the exchangeable to total manganese ratio. Glacial drift in both Denbighshire and Derbyshire tended to mask the regional variations due to geological features.

Limitations of stream sediment sampling in areas of transported overburden were also demonstrated by Holman (1959) in Nova Scotia, when drainages in a 10,000 square mile area were sampled and analysed for lead and zinc. The area was covered mostly by glacial overburden and the results did not reveal any patterns that might be related to bedrock.

To overcome these problems in areas of transported overburden, samples have been taken directly of the rocks. For example, in the Redlake-Landsdowne House area of Ontario the Geological Survey of Canada sampled some 25,000 square miles on an average of one sample every 3½ square miles. Results show that copper increases from 10-50 ppm through the acid to basic rock sequence, whereas zinc has a mean in all rocks in the region of 30 ppm (Holman, 1963). This lack of zinc variation might have been due to the bisulphate fusion attack used on the samples, which as has been shown by Harden and Tooms (1964), does not give a total attack on basic rocks.

These studies described above have established the viability of stream sediment sampling in both temperate and tropical climatic areas as a means of gaining geochemical information of geological features. They also show that an interpretation of the minor element distributions, variations due to secondary environmental features, contamination from human activities, and transported overburden must be considered. Variations that have been related to the geology have been found to be due to, variations in bedrock, facies change within bedrocks, mineralisation, and background variations related to metallogenic districts.

2.2.2. Geochemical stream sediment reconnaissance in Zambia

A number of studies of the secondary dispersion of the elements have been carried out in Zambia in order to optimise geochemical mineral exploration in the local environment.

Webb and Tooms (1958) reported on the secondary dispersion of copper and cobalt in the Copperbelt on the basis of an intensive soil, stream sediment, stream water and 'dambo'* sediment sampling programme. The results of this work showed that the technique of water sampling for heavy metal content developed in the temperate latitudes met with limited success, owing to the marked seasonal and even diurnal fluctuations of heavy metal content in the water in sympathy with the rainfall. Stream sediments and dambo sediments, particularly the minus 80-mesh fraction, gave dispersion trains of copper and cobalt of several thousand feet to a few miles from mineralisation. The dambo sediments were also found to concentrate both copper and cobalt in the organic rich surface layer, particularly around seepage areas. The cold extractable copper to total copper ratios were also much higher in the dambo sediment than in the freely drained laterite soils.

Govett (1958) worked on related problems in the Copperbelt area and reached somewhat similar conclusions, but added the significant facts (a) that the laterites and dambo sediments were dominantly residual, and (b) that copper was transported by local groundwater to the dambos and concentrated in the dambo sediment. He also noted a significant seasonal change in the copper content of the stream sediments, with a sharp rise at the beginning of the wet season followed by subsequent falling off due to dilution. Copper values also varied in proportion to the volume and velocity of the stream, the faster streams tending to keep the fine particles, which carry the copper, in suspension. The pH of the stream waters which ranged between 4.5 and 5.9 did not appear to have any effect on the copper in the stream sediment.

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*Dambos are poorly drained seasonal swamps, usually with no incised drainage channel, which form near the headwaters of the drainage system. Dambo sediment is composed of grey 'gley' clayey sand formed in a slightly reducing environment with a variable thickness of black organic material above and very white leached clayey sand below.

Jay (1959) investigated the secondary dispersion patterns of cobalt and uranium by detailed sampling of soils, stream sediment and water, and vegetation over limited but distinct geomorphological areas. He divided the stream sediments into three dominant types, sands, clays and oozes, the last of which are composed largely of ferric hydroxides which accumulate with the stream sediments in times of low water. The results showed that cobalt tends to be fixed preferentially in the oozes and secondly in the clays. Very little cationic cobalt was found in the stream waters and the pH had very little effect as long as it was below the hydrolysis level for iron. Velocity and slope of the stream and the nature and amount of erosion of the banks were found to be the main controlling factors on the length of the dispersion train. Uranium was found to be concentrated in the gley soils of the dambo sediments, while in the stream sediments the uranium distribution was largely controlled by the formation of complex carbonates.

Watts (1960) investigated the secondary dispersion patterns of niobium, which occurs in the Feira carbonatites in southern Zambia. In order to develop reconnaissance and prospecting methods, detailed sampling and size analyses of stream sediments, soils, stream waters and rocks were carried out. The results of this study indicate that pyrochlore is the dominant niobium bearing mineral. This mineral does not break down chemically very easily and the high pH of the Feira area militates against the formation of niobium cations. Therefore, the dispersion of niobium tends to be largely mechanical. After enrichment in the surface layers of the soil, due to leaching of soluble material, the pyrochlore is transported to the streams by a combination of soil creep and sheetwash. Anomalous dispersion trains in the stream sediment can be located in the minus 80-mesh fraction a few miles downstream from the mineralisation. The availability of pyrochlore in the fine fractions is probably a combination of the initial fine grain size and comminution. The coarser fractions and heavy minerals are more useful for locating specific mineralisation, especially as they give better contrasts. Zinc, which is associated with the niobium in the carbonatites, has its usual high mobility restricted by the strongly alkaline environment (Watts, 1960).

All the above studies have dealt principally with the dispersion patterns derived from possibly economic mineral deposits, but they have not dealt with the dispersions of elements derived from different lithologies which might be encountered in regional geochemical work. In order to throw more light on this subject, Harden (1962) carried out a regional geochemical orientation study in the Nyawa area in southern Zambia which is underlain by a norite body intruding biotite gneiss, and mixed horneblende and biotite schists. The rocks, soils, stream sediments and waters were sampled in detail and analysed for Co, Cu, Ni and Zn. They were mostly analysed using the potassium bisulphate fusion method. This method, however, did not give a total extraction of the Co, Ni and Zn due to these elements being held in the mafic minerals which did not break down completely on fusion. Total extraction was accomplished using a hydrofluoric/perchloric acid attack.

The results of this work show that cobalt, nickel values and the Ni:Zn ratio all gave a positive indication of the streams draining the norite body. Copper and zinc values change very little over the different lightologies. No significant patterns were found on the gneisses and schists. The minus 80-mesh fraction of the stream sediment was found to give nickel dispersion trains related to the norite up to 3 miles using the total attack method, whereas cobalt gave a train of only 2 miles. This was due to cobalt being concentrated dominantly in the coarse fraction where it was held by hard ferric and manganese nodules which formed in the poorly drained areas of soil overlying the norite. Harden also suggested that the ratio of the partial nickel extraction method to total nickel content might be a useful way to differentiate sulphide nickel anomalies from anomalies due to basic or ultrabasic rocks. In the former case the ratio should be much higher. Although this was shown to be true in dry climates, when mechanical breakdown was the dominant weathering agent, it was not true in wetter areas where the nickel has been released from the primary silicate mineral lattices and is in ionic form in the soil or drainage sediment (Wilding, 1965). Once the nickel is in ionic form it is impossible to tell its origin. Wilding suggested using Cu:Ni ratio and arsenic and selenium as possible pathfinders to nickel sulphide mineralisation when in association with ultrabasic rock units.

The culmination of the earlier studies in Zambia was the preparation of regional geochemical maps for 10 elements including cold extractable copper (Webb et al, 1964). This survey covered an area of some 3000 square miles in southern Zambia. The minus 80-mesh fraction of some 4000 drainage sediment samples was used as the sampling medium. The main conclusions have been mentioned in Chapter 1 and are expanded in the following:

(a) The major geological units are associated with broadscale patterns of variation in the range and mean concentration levels for several metals. The patterns are evident in both mineralised and barren formations.

(b) In ground underlain by the unmineralised formations, the patterns mostly appear as variations in the level and range of normal background values, and are related to the lithology and composition of the bedrock.

(c) Analyses of rocks, soils and stream sediments from the same areas show that similar trends in metal content are evident in all three materials. In one feebly mineralised area, however, no pattern was seen in the metal content of the soils and rocks; the sediment pattern may, therefore, be due to metal predominantly derived from minor quartz veins and ironstones which are widely distributed in this area.

(d) The degree of weathering, the nature of the surface drainage system, and the sample type, are also more or less closely related to topography. The influence of these features on the major geochemical patterns, at least, appears to be correspondingly slight, and certainly does not override the dominant geological control.

(e) Rock and soil samples are generally representative of a small area in the vicinity of the sample site, while the stream sediment represents an approximation to a composite sample of the catchment area. Limited data for rocks and soils confirm that the patterns obtained by sampling these materials would have been more erratic than those obtained by sampling the stream sediment, particularly in areas of heterogeneous lithology.

From the results of the different geochemical studies carried out in Zambia previous to 1964, it became apparent that there were marked minor-element background variations in drainage sediments which appeared to be related to presence of a metallogenic province or district rather than different rock types or secondary environmental considerations (Table 1, Webb et al, 1964). In particular, copper

Metal	Feira Area		Copperbelt Area			Mpika Area	Zambesi Area	
	Karroo sandstone	Basement gneiss and schist	Basement schist and quartzite	Granite	Katanga	Katanga (undifferentiated)	Quartzite	Paragneiss
	Range and geometric mean metal content (ppm) in minus 80-mesh fraction of stream sediment derived from above mentioned rocks							
Cu	25-130	5-90	75-280	65-230	60-90	2-120	7-45	4-28
	45	25	155	135	75	20	20	11
Co	<5-13	<5-17	12-35	<5-220	13-30	<5-70	<5-15	<5-15
	10	11	17	35	14	11	11	10
Sr	45-370	50-900	27-70	20-60	32-80	nd-180	10-140	10-150
	140	197	45	45	60	11	70	75
V	13-250	18-270	10-50	<2-85	<2-16	<2-220	<2-110	<2-220
	40	55	17	20	13	15	30	30
Mn	215-4200	320-4200	230-2700	300-1600	420-1200	12-800	320-3200	250-4000
	575	1200	480	725	710	65	1020	795
No. of samples	18	78	11	16	8	66	11	21

Table 1: Regional differences in trace metal content of stream sediments

is increased three to four times in the Copperbelt area and cobalt slightly higher; strontium is two to three times in the Feira carbonatite area and vanadium about twice (Webb et al, 1964).

Schiefler (1967) investigated the geochemical aspects of copper, tin and some other elements in relation to mineralisation in Lunga Basin to the north-west of Lukanga Swamp. Past findings concerning the secondary distribution of copper was confirmed such as the sorption of copper in dambo soils by organic and clay complexes, and the migration of copper in residual ferralitic soils and dambo sediment downslope from mineralisation. In addition, copper was found to generally increase with depth down the soil profile over mineralisation but tended to be concentrated in laterite layer over non mineralised background areas, and copper background level in soils and drainage sediments tended to be higher over argillaceous compared to granitic rock units. Analysis of granitic rocks, soils and drainage sediments for tin indicated that tin was enriched in the soils, dambos and active stream sediments compared to the underlying rock units. This feature suggested that tin was in a resistate mineral form, probably cassiterite and concentrated by the leaching of the major minerals and eluviation of the finer particles down the soil profile. Schiefler also concluded that there was probably no tin mineralisation in the area because the regional distribution of tin values in drainage sediment appeared fairly uniform.

2.3. DATA PROCESSING

The manipulation and evaluation of a large quantity of numerical multivariant data is extremely difficult and tedious. In the context of geochemical reconnaissance data, where noise due to sampling and analytical errors are relatively high, it may be difficult

(a) to identify and interpret trends of variation and (b) to visually correlate the element patterns and interpret any associations in terms of the primary and secondary features controlling the minor element distributions. Since the advent of computerised data handling techniques, various mathematical and statistical methods have been adapted and developed for the geological and geochemical data to help solve some of these problems.

Two main methods of analysing single variable or element areal trends in data have been used in geology, namely polynomial trend surface analysis, and rolling mean or moving average analysis.

2.3.1 Trend surface and moving average analysis

Trend surface analysis uses the criterion of least squares to develop a polynomial equation best describing the areally distributed data. Increasing the degree of the polynomial equation increases the complexity of the surface. Trend surface analysis has been applied increasingly to geological data. Text books describing its use and applicability are now available (Krumbein and Graybill, 1966. Chapters 12, 13).

Moving average analysis has been developed largely for evaluating gold ore reserves from gold assays in the South African gold mines (Krige and Ueckerman, 1963). It was used largely for the smoothing of the gold assay data which has a notoriously high sampling error and variance between adjacent samples, making it difficult to contour and evaluate ore reserves. The two dimensional moving average is simply an extension of a one dimensional moving average technique. Average values are computed from adjacent samples in defined small search areas within the sampled area as a whole. The resultant map of average values can then be contoured and overall trends seen more easily. The size, shape and degree of overlap of the search areas are the important parameters controlling the degree of smoothing and the statistical and actual significance of the trends defined. They should be selected on a basis of the distribution of the sample points and the nature of the patterns expected (Krige, 1966).

Polynomial trend surface analysis and moving-average analysis, referred to as rolling-mean analysis by Garrett (1966), have both been used to evaluate the results of the broad scale sampling in Sierra Leone already described in the earlier section 2.2.1., by Garrett (1966). A comparison of the different methods of interpretation and presentation indicated: (a) that both trend surface, and moving average analysis convey essentially the same broad regional patterns as conventional means of presentation but the trends are easier to see from a contoured type of map, (b)that the moving average surface was more faithful to the data than the cubic trend surface analysis, and (c) that polynomial trend surfaces are not necessarily a faithful model of the data and wide areas occurred where the trend surface was systematically too high or low.

Subsequent to Garrett's research, the use of various statistical techniques were evaluated using the regional geochemical data from the United Kingdom, already described in section 2.2.1., by Khaleelee (1969). The use of polynomial trend surface analysis was not considered to be a useful technique for indicating regional trends, since the data did not fulfil the various conditions essential to the correct application of trend surface analysis. For example:

(a) The optimum number of samples which may be significantly processed with present programmes is thought to range between 20 and 300 (Agterberg, 1964). The United Kingdom regional areas included 900 - 1000 samples.

(b) Inhomogeneities in sample distribution may induce polynomial trend surfaces bearing little relation to geological trend (Nordeng, 1965). The U.K. sampling tends to be clustered at stream intersections and inaccessible areas, and those with little surface drainage are poorly sampled.

(c) Biased and geologically unfeasible surfaces may be fitted to data including clusters of high and low values, particularly on the higher (greater than third degree) order surfaces (Krumbein and Graybill, 1966). The U.K. data frequently exhibit discontinuities of element level with clustering of high and low values.

(d) Trend surface is most applicable to homogeneously distributed data and where data levels change in a continuous manner. Regional minor element data change relatively sharply in level over different lithologies or other features controlling its distribution (Khaleelee, 1969). Moving average analysis was therefore used to smooth the data.

The moving average programme used was written by Khaleelee (1966) and adapted to plot the moving average parameters on a Calcomp plotter (Khaleelee, 1969). Khaleelee used a square search area of 44 Km^2, which gave a range of about 4-10 samples per search area. This size search was found to reduce the variability of the data without excessive smoothing compared to other search area sizes. A search area overlap of 50% was used because:(a) it was found to give adequate results, and (b) larger overlaps generated a greater number of moving average values than could be included on a single Calcomp magnetic tape. Data with positively skewed distributions were log transformed in order to approach a more nearly normal distribution. Three parameters for each minor element were plotted, namely moving-average, z-values and variance ratio. Where the moving average value is given by:-

$$\overline{M} = \sum_{N}^{i=1} X_i$$

where: $\overline{M}$ = moving average

ΣX = sum of all sample values within the search area

N = number of samples within the search area

where the z-values Z_V are given by:-

$$Z_V = \frac{\overline{X}_T - \overline{M}}{\sigma_T}$$

where: $\overline{X}_T$ = overall mean for all the data

$\overline{M}$ = moving average

σ_T = overall standard deviation

and the variance ratio V_R is given by:-

$$V_R = \frac{\sigma_M^2}{\sigma_T^2}$$

where: σ_T^2 = total variance

σ_M^2 = variance of samples within the search area.

The results showed that the moving average and z-values indicated essentially the same patterns as colour symbol maps. They gave, if anything, rather more detail than colour symbol maps, especially for minor elements with small concentration ranges. The variance ratio tended to be high along boundaries of the different primary and secondary features affecting the minor element patterns, thus adding information and aiding interpretation by indicating possible positions of geologic contacts and boundaries. The results of the moving average technique were more quickly available and easier to interpret than the colour symbol maps.

2.3.2 Factor analysis

Interpretation of features controlling minor-element variations from regional reconnaissance drainage data is extremely difficult from the distribution of only one variable because there is usually more than one controlling feature. The multi-element analyses, described in the earlier studies, have been carried out partly in an attempt to overcome this problem since controlling features might be more readily identified by associations of characteristic elements. It is difficult, however, to visually consider the regional variations of more than two elements at once and impossible to visually combine more than two elements into a single variate. Factor analysis was introduced in an attempt to overcome this difficulty by re-expressing the variates in terms of theoretical associations. These associations are based on the correlation coefficients between the variates. The method can use the correlation coefficients between either the variables (R-mode analysis), or the samples (Q-mode analysis). The R-mode method reduces the data to an association of variables (minor elements), and the Q-mode method reduces the data to an association of samples. It should then be possible to infer the controlling features from these associations on the assumption that they are reflecting the controlling features.

Factor analysis was first applied in the geological sciences to sedimentary petrological studies (Krumbein, 1957). Since then a number of studies using factor analytical methods have been made. For example, factor analysis has been applied to a heavy mineral provenance study in the Gulf of California and in the Orinoco-Guyana shelf (Imbrie and Van Andel, 1964). This work demonstrated, from a set of complex data, the existence of simple relations corresponding to zones of littoral transport.

Factor analysis was first applied to regional stream sediment geochemical problems to the data from the schist belts in Sierra Leone already described in Section 2.2.1. by Garrett (1966) using a Q-mode factor analysis programme written by Manson and Imbrie (1964). Its use effectively reduced the number of maps required to represent the data to three factors from thirteen minor elements. These three factors could be related to basic schists, and metal poor and metal rich granite facies. The communality, or extent to which the data variability of each sample could be accounted for by the chosen components or factors could be used as a possible measure of anomalies indicating mineralisation. That is, samples with low communalities show poor correspondence to the chosen components. In some cases samples with low communality drained areas of suspected mineralisation.

Concurrent with the writer's research, the use of Q- and R-mode factor analysis was evaluated on the United Kingdom regional stream sediment data already briefly described in section 2.2.1. (Khaleelee, 1969).

The programmes used in this comparison were the Q-mode by Manson and Imbrie (1964) and an R-mode by Garrett (1967). A comparison was also made between R-mode solutions extracted from the above programmes.

The comparison of the factor solutions between the different modes indicated that, for most regional geochemical problems, R-mode was likely to be a more useful method than Q-mode for a number of reasons. A practical but important consideration is that with Q-mode only a limited number of samples in the order of 100-300 can be processed with present available programmes, and this number cannot be significantly increased with present computer memory stores.

Any number of samples, however, can be processed using the R-mode technique. Data from one of the U.K. regional surveys which included some 900-1000 samples, were split into 3 subsets of 100 samples each with a representative number of samples from each lithology. Q- and R-mode factor analysis was carried out on each subset. The solutions indicated that the R-mode method gave more stable minor-element associations than the Q-mode method. The Q-mode solutions were also more difficult to interpret since the factors are defined in terms of sample end members which are of extreme composition and often bear little relation to the composition of most of the samples. The R-mode solution, on the other hand, defines the factors in terms of element associations with a factor loading on each element which represents the strength of correlation of an element with a factor. These factor associations can be more readily related to geological and secondary environmental features of known minor element content.

R-mode solutions using Manson and Imbrie's (1964) and Garrett's (1967) factor analysis programmes were also compared using unrotated orthogonal, rotated orthogonal and rotated oblique techniques. The main differences between the programmes lies in the method of obtaining oblique solutions. Garrett's programme uses the Promax method described and written by Hendrickson and White (1964) which powers the rotated matrix in order to obtain obliquity, whilst the Manson and Imbrie programme chooses one of the variables as an end member in order to attain oblique structure. Results using the different solutions showed that rotated orthogonal solutions of both programmes were identical except for the order of the factors. Both rotated solutions gave more significant results than the unrotated solutions. The Promax oblique solution gave identical factor associations to the rotated solution except that the contrasts between the high and low factor loadings were heightened. The Manson and Imbrie oblique solution, however, was markedly different from both the Promax and the rotated solutions and the similarity between the factor solutions of the three subsets was not as close as that observed in the rotated factor or Promax factor solutions. Khaleelee concluded that Garrett's R-mode programme was preferable to the Manson and Imbrie programme. The Promax oblique solutions were used in preference to the rotated solutions on the grounds that they may more closely represent the correlations between trace element associations of the geochemical data, and on the theoretical grounds that in the geochemical environment controlling factors defined by minor elements are probably correlated. Garrett's programme was also preferred because it includes an R-score option by which individual samples can be related to the factor associations with scores. A high sample factor score indicates a strong control of the minor elements of the sample, by that factor. Plotting and contouring of these factor scores on individual factor maps proved to be a useful indication of the areas of influence of the different factors.

The results of R-mode factor analysis as applied to the U.K. regional data showed that the original associations already interpreted from the data (section 2.2.1.) were brought out as factors. In addition, there was a Cr, Fe, Ga, Ti, V association evaluated from data in North Wales, the English Peak District and a modified version in S.W. England which has not been previously recognised. The distribution of the R-scores in particular factor associations occurred in areas already noted as the controlling features of that association. Samples with high scores in the Cr, Fe, Ga, Ti, V association were found to be related to argillaceous rich facies.

Further detailed sampling and analysis of rocks and soils was carried out over selected factor score patterns. Factor analysis of these results gave similar factor associations to the drainage sediment associations, and the Cr, Fe, Ga, Ti, V association could be related directly to the clay rich mineralogy of the rocks.

It was concluded that R-mode factor analysis was a useful technique for the recognition of the main element associations from regional geochemical data. From these associations the various controls influencing the minor element content of the stream sediment, such as bedrock type, mineralisation and secondary environment, can then be postulated. The computation and plotting of R-scores for each sample was a useful technique for showing the distribution of these controlling features.

CHAPTER 3

DESCRIPTION OF FIELD AREAS

3.1 CENTRAL ZAMBIA

3.1.1. Geology of Central Zambia

The geology of Central Zambia consists largely of the Precambrian Basement Complex and Katangan System, with minor areas of Tertiary Karroo sediments, basalts and carbonatites (Fig. 2).

The pre-Katangan Basement Complex outcrops mostly in the east and south of the field area and is composed mostly of granite, granite gneisses and paragneisses, and relatively high-grade metamorphic schists and quartzites. Ultrabasic and basic rocks, including some metavolcanics, outcrop to a limited extent in the east of the area. From radiometric dating methods and structural considerations there is evidence that there are at least three major units present, although stratigraphic continuity and evidence of unconformities have been destroyed by intense and repeated deformation (Cahen and Snelling, 1966).

Katangan rocks outcrop mostly in the north and west of the field area and are composed of clastic sediments, limestones and dolomites. They are metamorphosed to various grades, and intruded by gabbros and norites in some places but, rarely intruded by granitic rocks.

Karroo rocks are preserved mainly in the downwarped rifts such as the Mid-Zambezi, Luangwa and Lunsemfwa valleys. They are composed of continental clastic sediments derived from the underlying Precambrian rocks. Basalt lava flows were extruded around Livingstone over an extensive area of the Mid-Zambezi valley during this period.

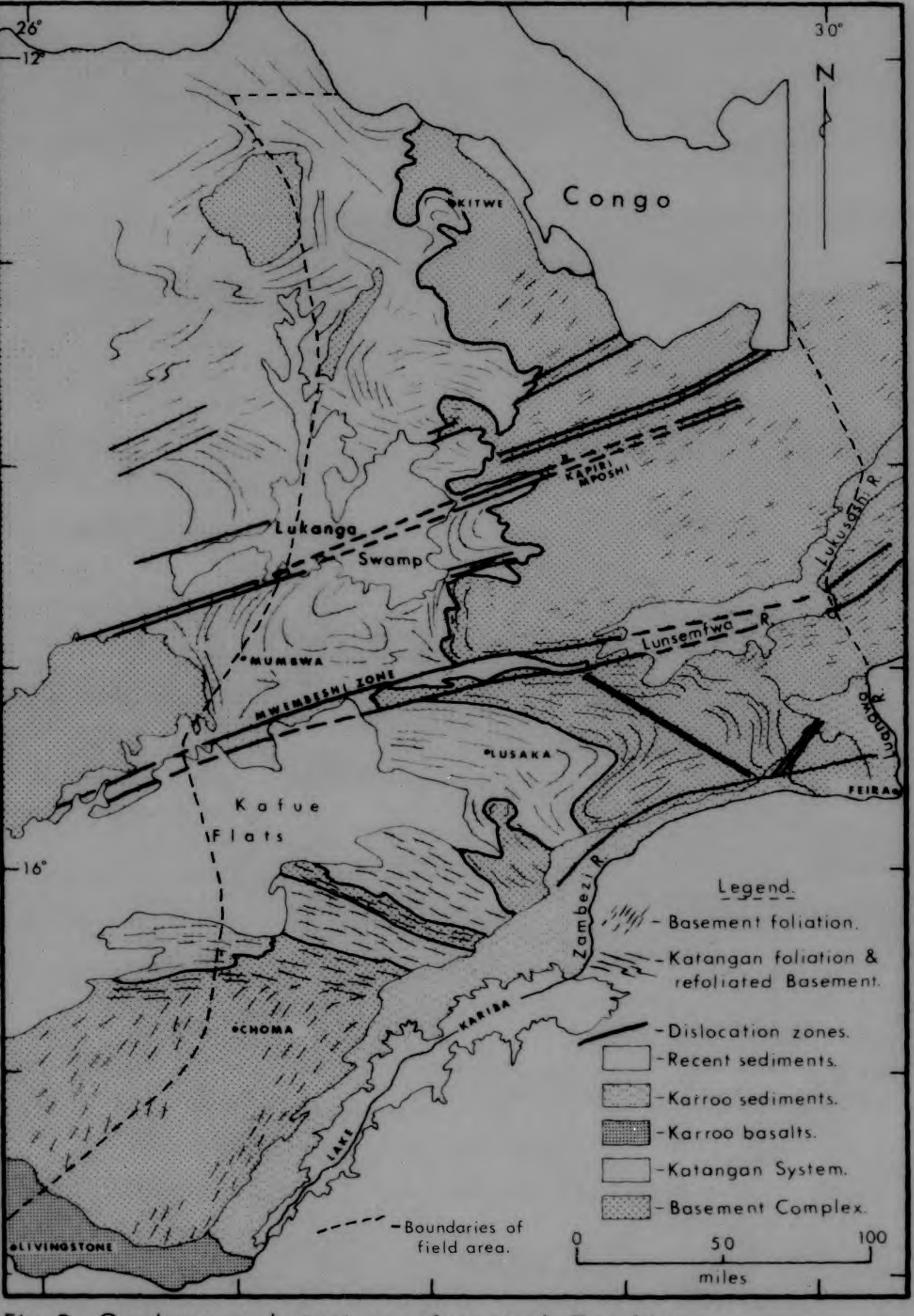

Fig: 2 Geology and stucture of central Zambia.
(after deSwardt 1965).

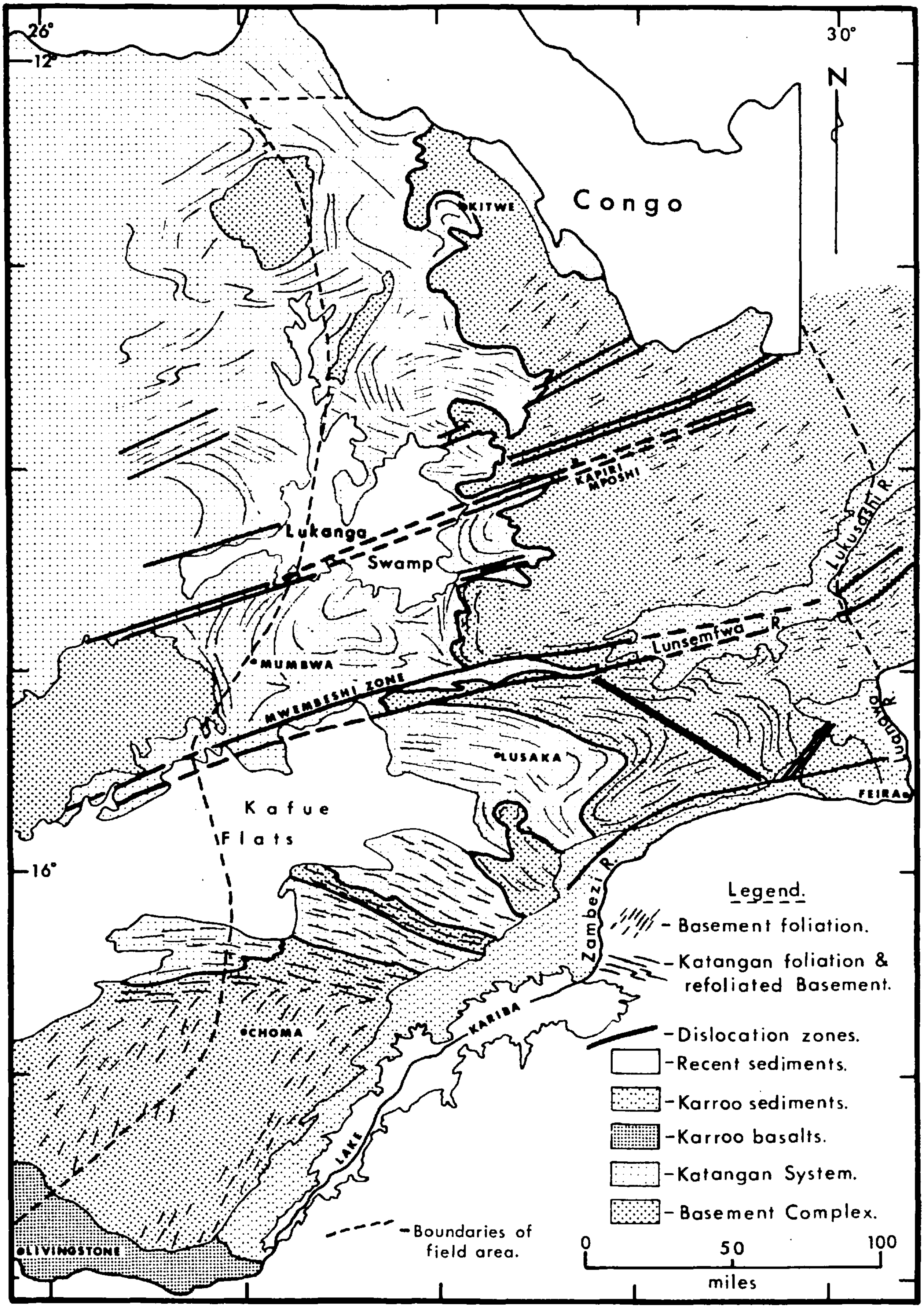

Fig: 2 Geology and stucture of central Zambia.
(after deSwardt 1965).

3.1.2. Structure

The main structural alignment of the Basement Complex is east-north-east and is related to the Irumide orogeny, and has clearly been superimposed on earlier trends. Pre-Irumide trends vary from west of north to north east, and may explain these trends in the Basement of the Copperbelt.

During the post-Katangan Lufilian orogeny, basement rocks in the area around Lusaka and south towards Livingston and Choma were drawn into structural parallelism with the overlying Katangan rocks and extensively refoliated. In the Copperbelt, Lufilian metamorphism was of lower grade owing to the higher level of the crust in the north, and the Katangan rocks became detached from the Basement and refoliation of the latter weaker and more localised.

East-north-east zones of dislocation, along which considerable displacement appears to have taken place, occur along the Mwembeshi dislocation, which is north of Lusaka and runs east-north-east into the Lunsemfwa valley rift, and the Kapiri Mposhi dislocation zone which runs east-north-east and west-south-west through Kapiri Mposhi. Considerable reorientation of earlier trends in the Katanga metasediments and to some extent in the Basement parallel to these dislocation zones, has taken place (de Swardt et al, 1964).

3.1.3. Metallogenic provinces and districts

During the course of mineral exploration and mining activity in Central Africa, certain metallogenic provinces and districts have become clear. These provinces and districts are mostly associated with the Precambrian basement and Katangan rock units. Five of these metallogenic provinces and districts have been defined and noted to occur in Central Zambia as follows (Fig. 3) (Reeves, 1963; de Kun, 1965):

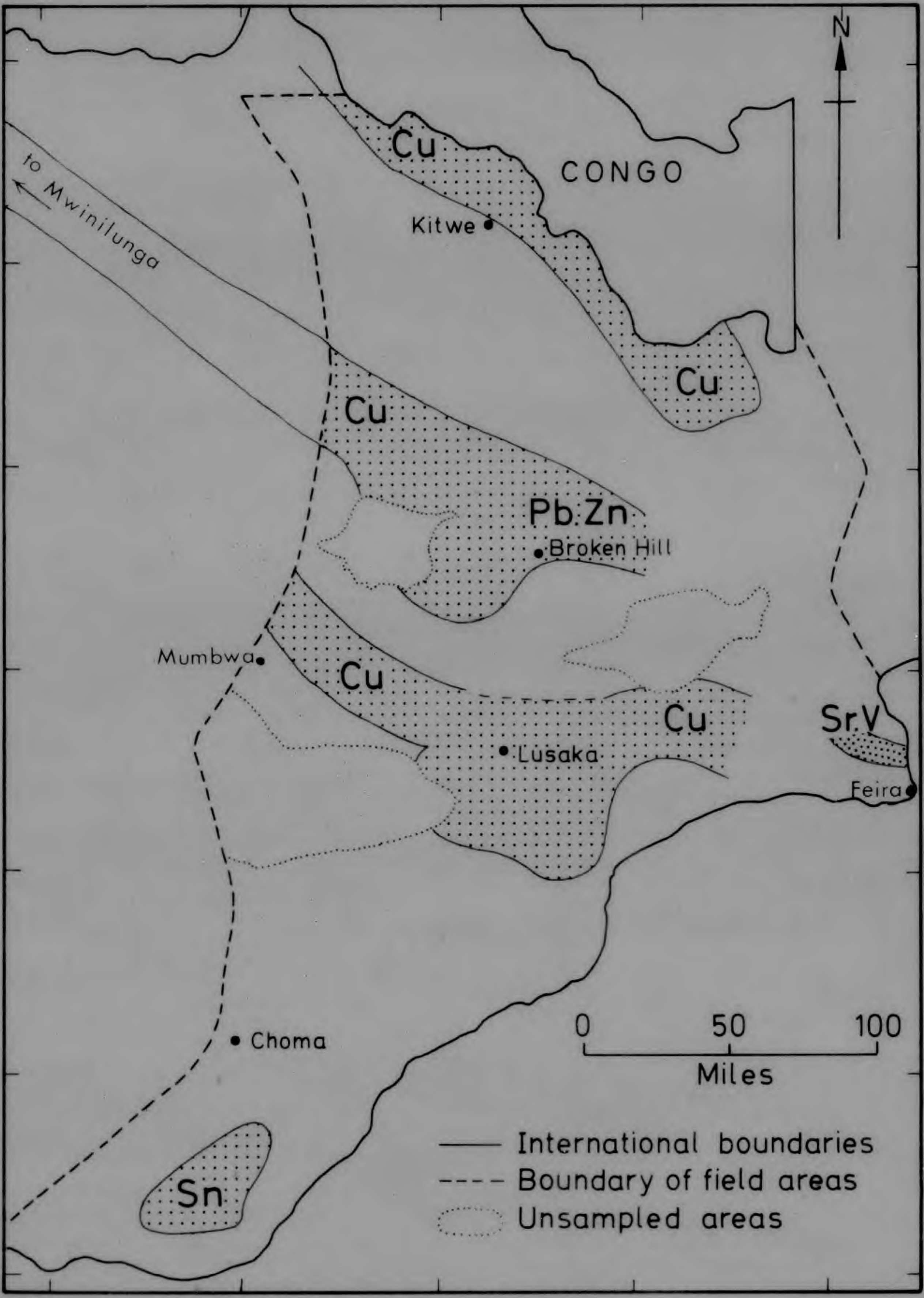

Fig: 3 Metallogenic provinces in Central Zambia. (After deKun 1965, Reeves 1963).

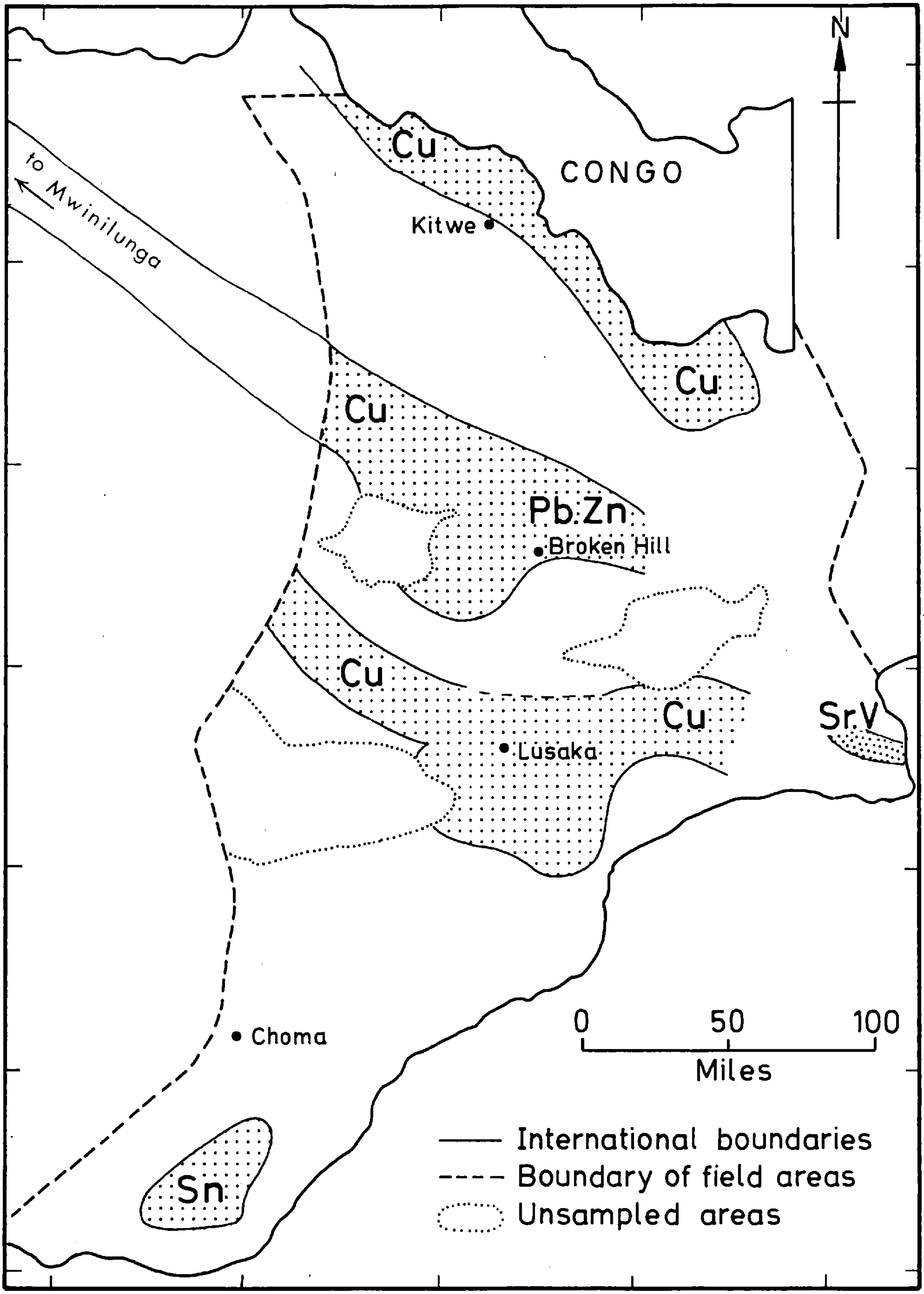

Fig: 3 Metallogenic provinces in Central Zambia. (After deKun 1965, Reeves 1963).

(a) the copper, cobalt province in the Copperbelt in the north of the field area (Fig. 3). Most of the large mineral deposits in the Copperbelt are stratiform copper sulphide deposits associated with the Lower Roan formation of the Katangan System, although there are also some minor epigenetic copper sulphide vein deposits in both Katangan and Basement rocks.

(b) A metallogenic district of hydrothermal copper, lead and zinc mineralisation trending from Mwinilunga southeast to Broken Hill mostly in the Katangan rocks. In the Broken Hill area lead and zinc mineralisation is dominant but towards the northwest copper mineralisation is more prevalent.

(c) A metallogenic province of copper mineralisation extending from Mozambique west-north-west to Lusaka and Mumbwa in rocks of pre-Katangan and Katangan age.

(d) A metallogenic district of tin mineralisation extending for some 60 miles in a north-east to south-west trending belt in the area south of Choma. This mineralisation occurs in pegmatites and associated small placer deposits in the vicinity of the pegmatites. The mineralised pegmatites themselves appear to be derived from an ancient granitic mass which, due to repeated orogenies and metamorphic episodes in the area is now difficult to recognise (Matheson, G., Geol. Surv. Zambia, pers. comm.).

(e) Niobium, vanadium, strontium and rare earths occur in association with carbonatite intrusions. These carbonatite intrusions tend to occur in areas of rift intersections, for example in the Rufunsa River area just north-west of Feira.

3.1.4. Physiography and drainage

Central Zambia can be separated on the basis of two distinct physiographic features. A peneplained plateau, which is part of the Central African plateau (Dixey, 1944), and escarpment areas associated with the borders of rift valleys.

The peneplained plateau varies between 3000 feet above sea level in the south to 4000 feet in the north on the Zambia-Congo border. The country is flat with rolling hills and occasional ridges of quartzite about 200 to 500 feet above the general level of the land.

The escarpments parallel on either side the Zambezi, Lunsemfwa and Lukusashi river valleys. The peneplained plateau falls away relatively abruptly about 1500 to 2000 feet to the valley floors in a series of fault scarps. A very rugged terrain is formed by the steeply incised streams.

Central Zambia forms part of the northern drainage basin of the Zambezi River. On the plateau region the drainage is largely dendritic and only controlled by geologic structure to a limited extent. The streams rise on the plateau in low lying swampy areas known as 'dambos', which have characteristic acid, clayey soil type. A stream channel usually begins to form 1 to 5 miles down the dambo, but the essential pedological character of the dambo usually continues on either side of the stream channels until they reach the main drainage channels of 100 square mile catchments and over. Along the main river systems, in particular the Kafue River, very extensive areas, such as Kafue Flats and Lukanga Swamp, are covered by flood plain alluvial sediment.

At the edge of the escarpment the streams become deeply incised, often flowing parallel to the escarpment edge along rift faults before breaking over waterfalls and rapids to the main valleys The main rivers break through the escarpment areas in a series of rapids and gorges such as the Kafue gorge, where the Kafue River flows through the mid-Zambezi escarpment to join the Zambezi River.

3.1.5 Climate

Although Zambia lies within the tropical savannah belt, temperatures are lowered by elevation and, in general, range from 55° - 75°F on the plateau but tend to be warmer in the lower valley floors. The year can be divided into a dry and a wet season. The dry season occurs from May to October with cool, moderate temperatures in the winter months of June, July and August, sometimes with frosts at night. The temperature increases during September and it becomes hotter and more humid in October until the rains break in November. The rain season continues until April, and tends to reduce the otherwise high summer temperatures. The rain falls in heavy tropical showers of variable duration, often in afternoon thunderstorms. Rainfall averages over 45 inches to the north but is about half that amount in the south with an average of 25 inches. There is also a drop of about 10% in the number of days rain falls in the south compared to the north (Fig. 4) (Chaplin, 1954, 1955).

3.1.6 Pedology

The regional soil types of Zambia are controlled by physiography, rainfall and on a localised basis, by the geology (After Zambia Department of Agriculture, 1967). On the basis of physiography and climate, the soils can be divided into six main types (Fig. 5):

(a) ferrallitic soils in the high rainfall areas in the plateau areas of north central Zambia;

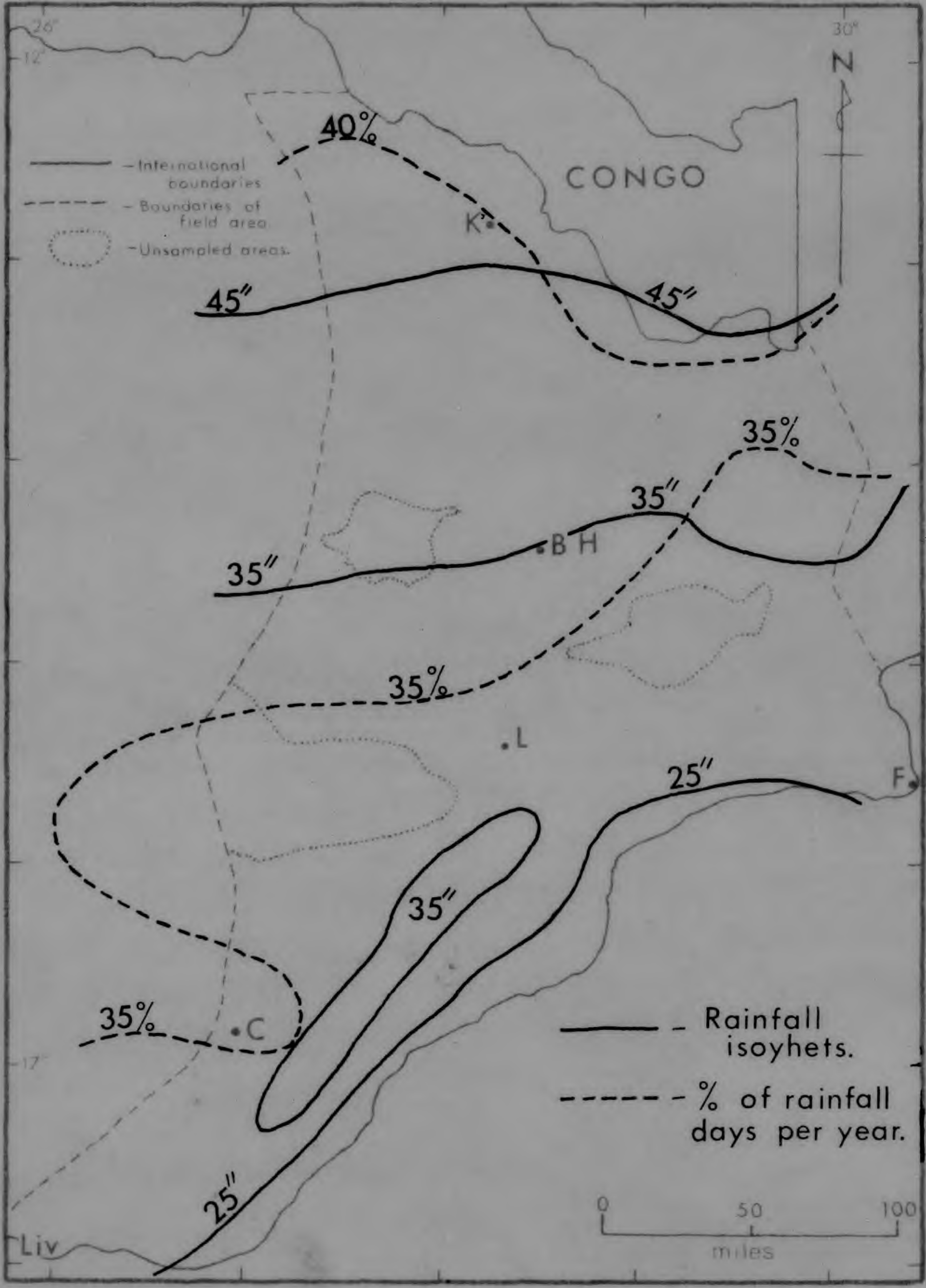

Fig: 4 Rainfall distribution and percentage of rainfall days per year in central Zambia (after Chaplin, 1954, 1955).

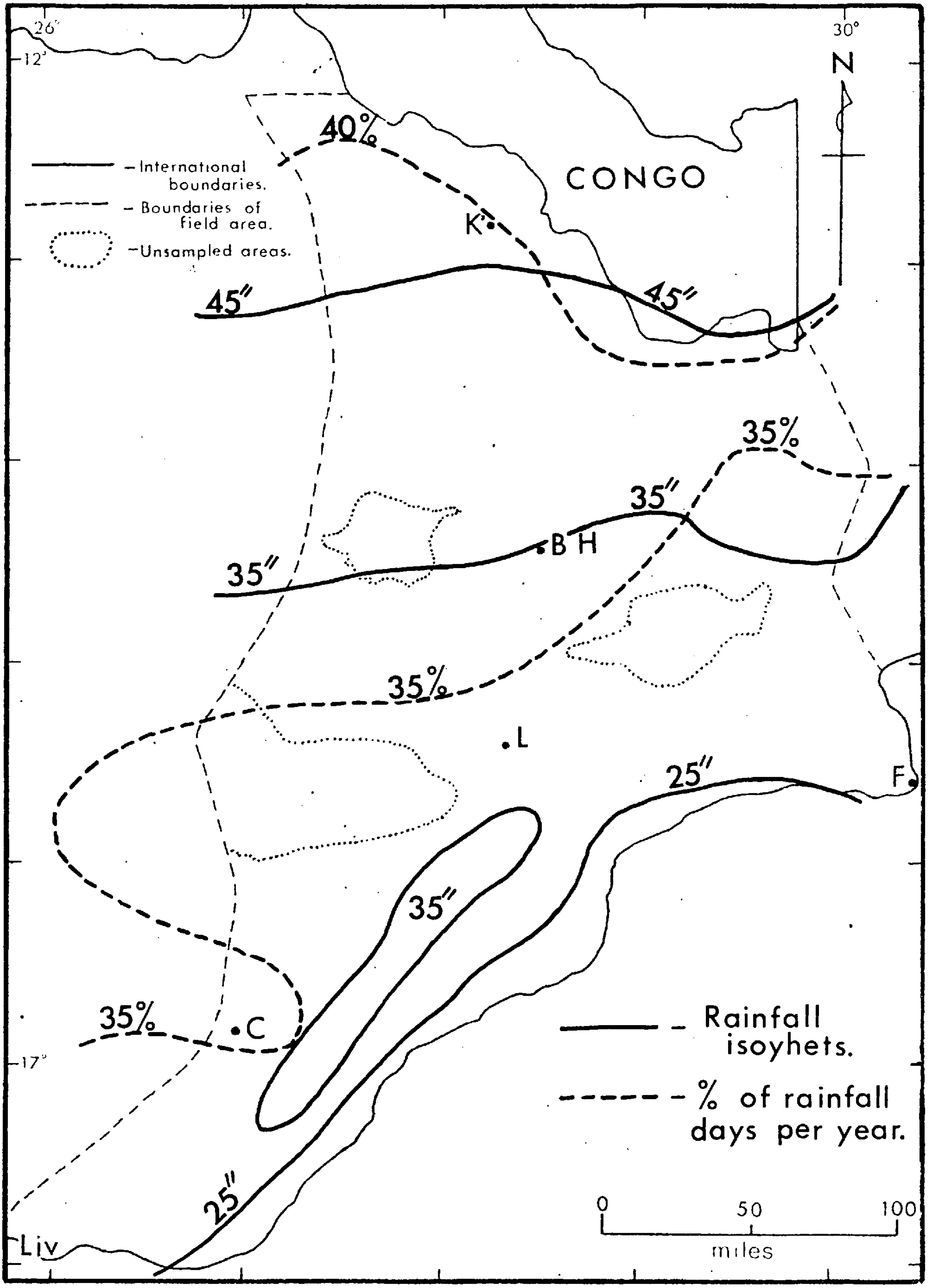

Fig: 4 Rainfall distribution and percentage of rainfall days per year in central Zambia (after Chaplin, 1954, 1955).

(b) fersiallitic or ferruginous tropical soils in the lower rainfall areas in the southern part of the Central Zambian plateau;

(c) ferrisols covering most of the central portion of the field area of intermediate rainfall;

(d) hydromorphic soils in swamps usually where seasonal flooding takes place such as the Kafue flood plain and Lukanga swamp;

(e) lithosols which form on the steep slopes in the escarpment areas;

(f) soils forming over carbonate rocks, and rocks rich in ferromagnesian minerals;

(a) Ferrallitic soils

Ferrallitic soils occur mostly in the high rainfall areas north of the 40 inch rainfall isoyhet. These soils have a low base saturation. They are acid, siliceous and have a low clay fraction consisting of kaolinite. They are highly leached, and often very deep, reaching depths of 50 or more feet. Their profiles tend to have a gradual transition between horizons (table 2(a)).

(b) Fersiallitic soils

Fersiallitic soils occur in the plateau areas in drier areas to the south of the 40 inch rainfall isoyhet. These soils have a relatively higher base saturation compared to the ferrallitic soils to the north and are usually only slightly acid. Although the clays present are dominantly kaolinite, they have a higher proportion of illite and montmorillonite. Their profile has similarly gradational horizons as the ferrallitic soils but tends to be darker and lacking the highly leached upper horizons (table 2(b)).

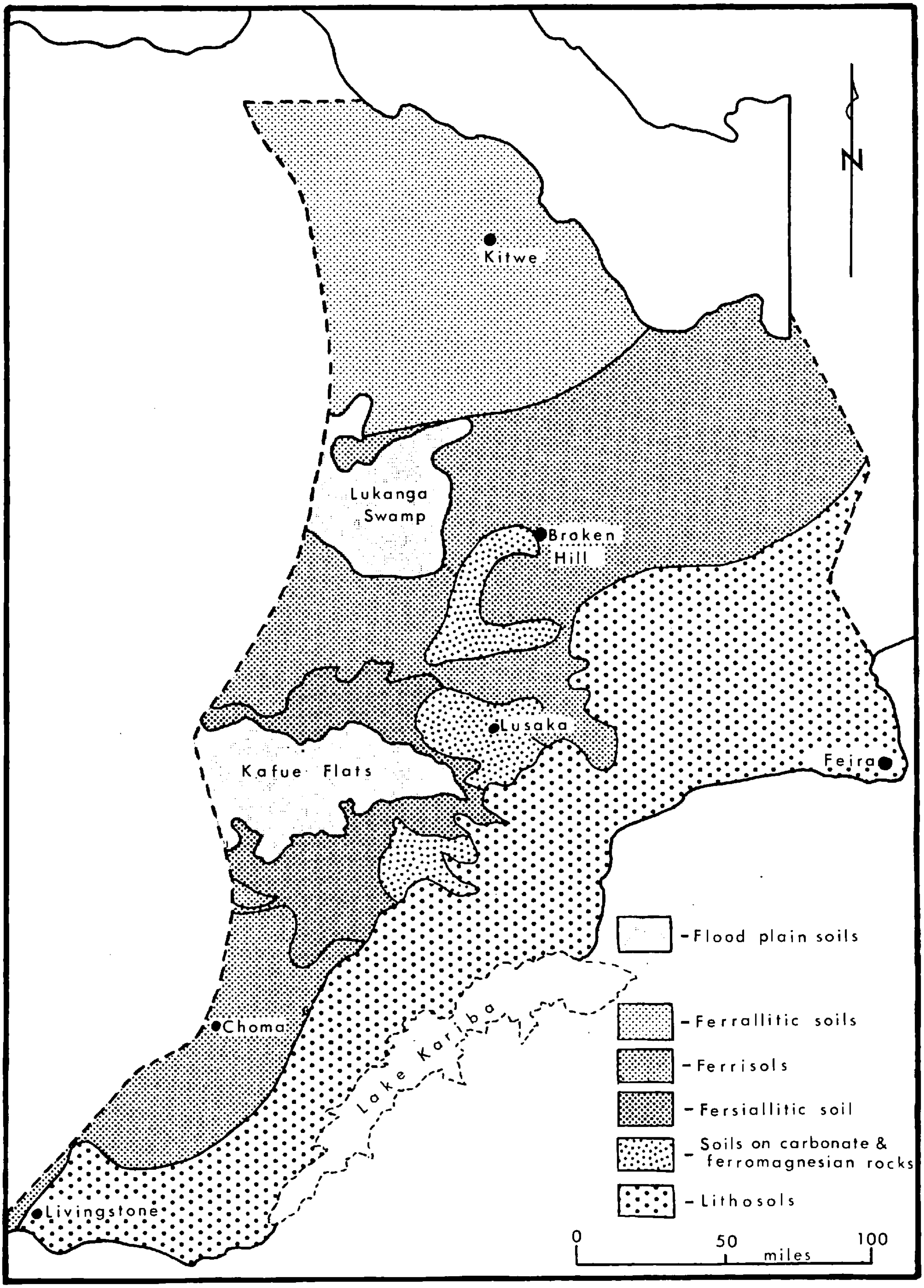

Fig: 5 Generalised soil map of central Zambia. (After Zambia Dept. of Agriculture, 1965)

Table 2

Soil Profiles

(after Zambia Dept. of Agriculture, 1967)

(a) Ferrallitic Soils

Depth	Horizon	Cation ex. cap.	% saturation	pH $CaCl_2$	Description
0"-6"	A_1	4.9	39	5.0	Dark brown, fine sandy loam; structureless; friable when moist.
6"-20"	B_1*	2.7	27	4.5	Yellowish red, fine sandy clay loam; weak to medium subangular blocky to fine crumb structure; friable when moist.
20"-60"	B_2*	2.6	19	4.6	Yellowish red fine sandy loam; weak to very fine subangular blocky structure, friable when moist.

Location of profile - Copperbelt, near Mufulira

Average rainfall per year - 50 inches

Bedrock - Biotite schist

*N.B. This soil horizon nomenclature is that used by soil scientists working in Zambia. Geochemists in the past have termed these horizons A_2 (Govett, 1958). Using a soil scientist's nomenclature, however, the A_2 horizon denotes a leached horizon relative to an A_1 horizon above. (D'Hoore, 1964). This is very rarely the case in soils in Zambia as the clay content usually increases with depth below the A_1 horizon.

Tabie 2 (continued)

Soil Profiles

(after Zambia Dept. of Agriculture, 1967)

(b) Fersiallitic Soils

Depth	Horizon	cation ex. cap.	% saturation	pH $CaCl_2$	Description
0-6"	A_1	5.7	93	5.3	Dark brown, loamy fine sand; structureless; slightly hard when dry
6"-16"	B_1	10.1	52	4.5	Yellowish red fine sandy clay loam; strong, fine subangular blocky structure; hard when dry
16"-32"	B_{21}	11.7	59	4.8	Dark red fine sandy clay; strong fine, subangular blocky structure; hard when dry
32"-60"	B_{22}	12.3	57	5.6	Red fine sandy clay; weak, fine, subangular blocky to massive structure; slightly hard when dry

Location of profile - South of Mazabuka

Average rainfall per year - 31 inches

Bedrock - Biotite schist

(c) Ferrisols

Ferrisols are essentially gradational in composition between the ferrallitic and fersiallitic soils (table 2(c)).

(d) Hydromorphic soils

Hydromorphic soils need not be considered on a regional basis in this description since in the areas where they occur in Central Zambia, Lukanga swamp and Kafue flats, the parent material is probably flood plain alluvial material, and stream sediment sampling in such an area would not be a viable method for the interpretation of the bedrock geochemistry. Residual hydromorphic soils, however, occur in all the dambo and drainage areas on the plateau where seasonal flooding takes place, due to the rise of the water-table to surface level. They are important, therefore, from a drainage sampling point of view on the plateau.

The freely drained plateau type soils grade in a catenary curve into the hydromorphic soils of the dambo areas. Hydromorphic soils cannot sustain tree growth and therefore the boundary between normal plateau soils and hydromorphic soils are usually clearly defined by the limits of tree growth around a drainage channel, or dambo. The upper few inches is sometimes strongly organic, even peaty; this is particularly true in the wetter northern part of the field area or in dambos in which the water is dammed in some way, thus forming a swamp. This organic horizon, however, is often absent, particularly in the drier southern parts of the field area. The main upper horizon, which is always present in a dambo, is a sandy clay or clayey sand which varies from 9 inches to 2 to 3 feet in thickness, and grades from grey and dark grey to bleached white clayey sand (table 2(d)). Except in areas of carbonate and basic or ultrabasic rocks, the pH in

Table 2 (continued)

Soil Profiles

(after Zambia Dept. of Agriculture, 1967)

(c) Ferrisols

Depth	Horizon	cation ex. cap.	% Saturation	pH $CaCl_2$	Description
0-3"	A_1	4.2	82	6.6	Very dark greyish brown fine sand; weak fine crumb structure; soft when dry
3"-17"	A_3	3.0	25	5.8	Brown loamy sand; structureless; soft when dry
17"-30"	B_1	3.6	39	5.9	Strong brown sandy loam; weak medium subangular blocky structure; slightly hard when dry
30"-48"	B_{21}	4.6	40	5.6	Yellowish red sandy clay loam; weak medium sub-angular blocky structure; hard when dry
48"-72"	B_{22}	4.5	46	5.9	Yellowish red sandy clay loam; strong fine sub-angular blocky structure; hard when dry; few thin patchy dark coatings on peds

Location of profile - West of Broken Hill

Average rainfall per year - 36 inches

Bedrock - Schist

Table 2 (continued)

Soil Profiles

(after Zambia Dept. of Agriculture, 1967)

(d) Hydromorphic soils

Depth	Horizon	Cation ex. cap.	% Saturation	pH $CaCl_2$	Description
0-1"	A_1				Very dark grey medium to coarse sand; structureless; loose when moist; Sharp boundary
1"-15"	A_2	3.6	83	5.5	Grey medium to coarse loamy sand; structureless; loose when moist; Sharp boundary
15"-48"	B_2	19.9	97	6.7	Grey fine sandy clay loam; weak coarse columnar structure when moist
48"-100"	B_3	30.4	100	8.0	Light grey sandy clay; massive; firm when moist; many fine light olive brown mottles; few medium calcium carbonate concretions

Location of profile - East of Lukanga swamp

Average rainfall per year - 35"

Bedrock - Alluvium of mixed source

these dambo soils tends to be slightly acid and their base exchange capacity is somewhat higher than surrounding soils.

(e) Lithosols

Lithosols occur on steep slopes such as are found in the escarpment areas wherever erosion tends to keep pace with weathering. They are usually very shallow and contain pebbles of the underlying parent bedrock (table 2(e)).

(f) Soils over carbonate rocks and rocks rich in ferromagnesian minerals

In areas of carbonate and basic and ultrabasic rocks, hydromorphic dambo soils are modified to brownish grey and respectively black clays with a high pH, often with manganese or iron oxide concretions. The plateau soils, where freely drained and underlain by these rocks, tend to be red and dark red clays with considerably increased base exchange capacity. They have little profile development and are often very shallow, particularly over carbonate units (table 3(a,b)).

3.1.7 Drainage Sediment

Drainage sediments encountered in the field area can be divided into two basic kinds which are controlled by physiography:

(a) dambo type sediment occurring in the drainages on the plateau, and

(b) active stream sediments predominantly of sand which occur in the incised streams of the escarpment areas.

Dambo sediments have been described in the previous section on hydromorphic soils. Dambo type drainage sediment, that is the grey clayey sand or sandy clay, is found to be present not only in the

Table 2 (continued)

Soil Profiles

(after Zambia Dept. of Agriculture, 1967)

(e) Lithosols

Depth	Horizon	pH $CaCl_2$	Description
0-5"	A_1	6.1	Dark reddish grey to weak red gravelly sandy loam, reddish brown when dry; moderate, fine angular structure; soft to slightly hard when dry; gravel composed of weathered mica schist and its saprolite clear boundary
5"-15"	C_1	6.7	Red gravelly, strong sandy clay loam; weak, fine granular structure; over 75% weathered mica schist and its saprolite; diffuse boundary
15"-42"	C_2		Weathered mica schist and its saprolite with red films on weathered faces; diffuse boundary
42"-60"	C_3	6.9	Weathered mica schist with reddish brown films on weathered faces

Location of profile - South of Choma

Average rainfall per year - 32 inches

Bedrock - mica schist

dambos themselves but also in practically all the drainage systems on the plateau, whether they are streams or dambos with incised drainage channels or even main rivers. It usually forms a relatively distinct sediment free from any organic material; organic material accumulates mostly in seep or swamp areas.

In the escarpment areas on the other hand, most of the drainages are steep incised streams and the grey clay fraction has for the most part been washed away by the sudden torrential rainstorms and subsequent flooding, leaving only well washed rusty yellow coloured sands and gravels. These are composed of quartz and rock fragments with a small proportion of silt fraction.

3.1.8 Geochemistry

Geochemical reconnaissance data from analyses of drainage sediment samples covering some 10,000 square miles of Central Zambia were made available by Chartered Exploration. These drainage sediment samples were collected and analysed during routine mineral exploration over a period of some seven years from the mineral concessions held by Chartered Exploration. The samples were analysed colorimetrically for Co, Cu, Ni, Pb and Zn and spectrographically for a variety of other elements. A comparison of element background levels showed that certain elements had different background values in different parts of the concession areas. Some of these background variations could be related to known geological features such as change in bedrock type and presence of mineralisation. In particular, higher copper background was noted in the Bancroft area and in the area east of Lusaka, both areas of known copper mineralisation, and high lead background was noted in the Broken Hill area. High copper, nickel and zinc background was noted in the Mtuga south area where basic rocks are the dominant lithology. High nickel background was noted in the area south of Lukanga swamp, but there was no known geological explanation for this increase.

These variations in background gave an initial encouragement to the provincial sampling programme because they indicated large scale minor element variations. Nothing is known, however, of the analytical accuracy of these results. In other words, the variations of minor-element level that occur over the whole period when the samples were taken and analysed, due to different sampling procedures, analysts and analytical methods. Little reliance, therefore, is placed upon them.

3.2 KADOLA AREA

3.2.1 Geology

Kadola area lies south of the Copperbelt and northwest of Broken Hill (see Fig. 1). The geology includes Basement and Katangan rocks (Fig. 6). Basement rocks include granite gneisses and schists which have been correlated with the Lufubu and Muva quartzites and schists. Overlying, less metamorphosed units have been correlated with Katangan units of the Copperbelt. These include the Lower Roan, composed of biotite quartzites and schist bands, Upper Roan limestone and dolomites, Mwashia Group of biotite and biotite muscovite schists, and Kakontwe limestone and dolomites with subordinate slates, phyllites and schists.

A small outcrop of serpentinite occurs at Jack's mine, just south of the Lukanga River, in association with amphibolite and gabbro emplaced at the Lower Roan-Lufubu schist contact. Amphibolite and

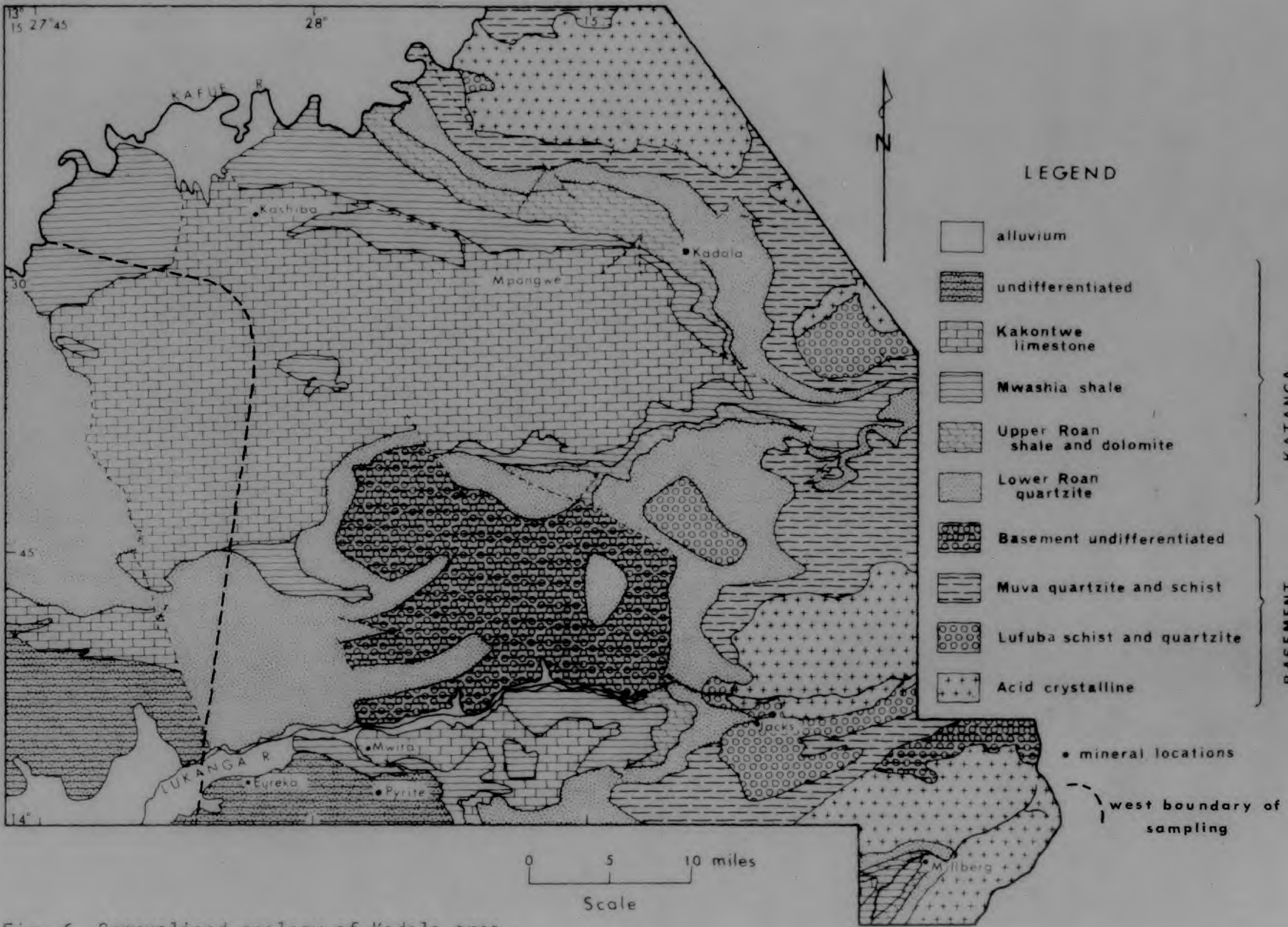

Fig: 6 Generalised geology of Kadola area.

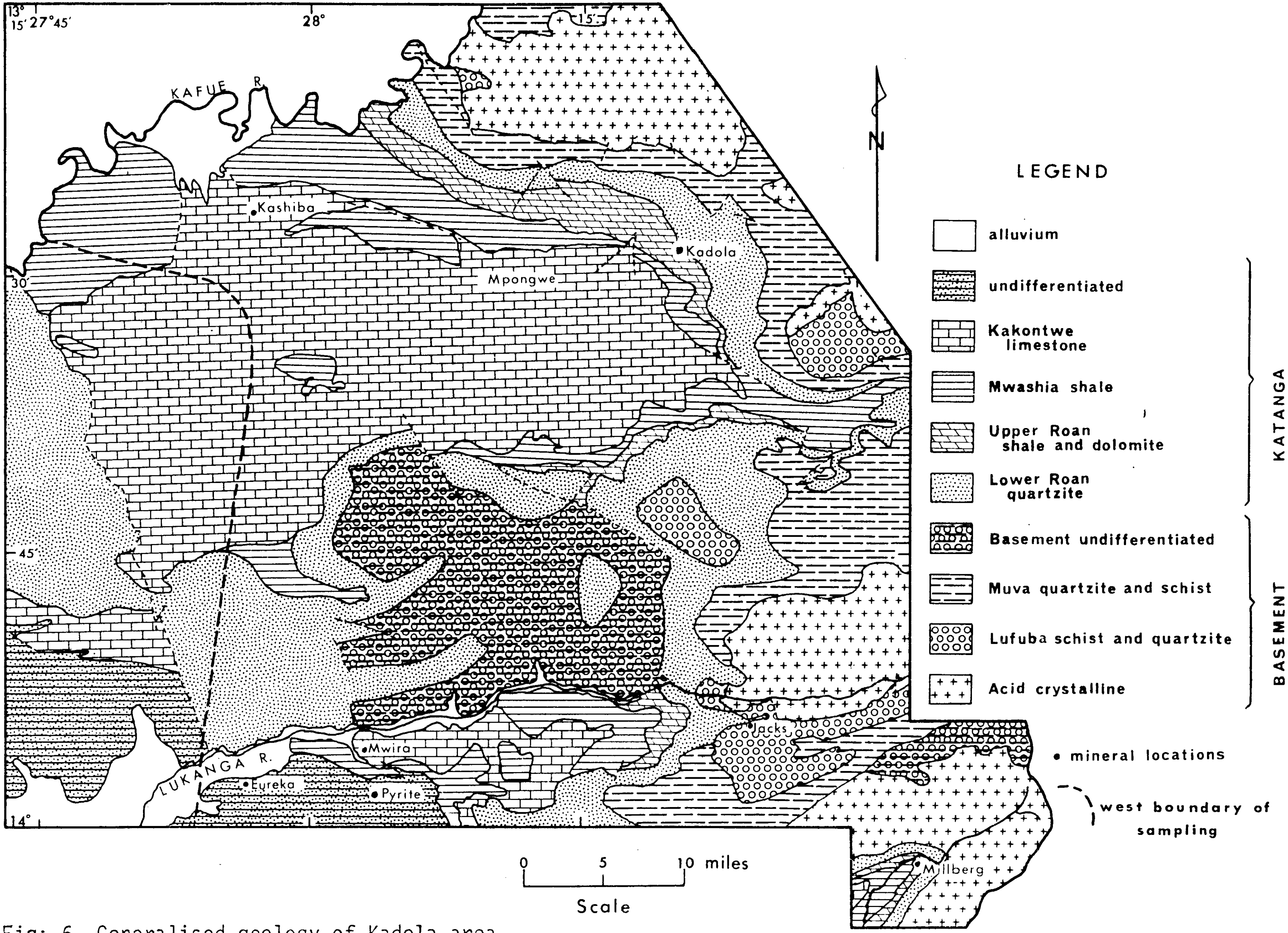

Fig: 6 Generalised geology of Kadola area.

gabbro also occur at Mwira mine, to the west of Jack's, emplaced in Kakontwe limestone.

Outcrop is poor except for the quartzite and carbonate units. The geology has largely been interpreted from soil characteristics which change over the different lithologies, and from aerial photo-raphs which show the distinctive vegetation patterns which occur over the different lithologies (Mendlesohn, 1961).

3.2.2 Structure

Katangan units outcrop mainly in the west and northwest of the field area. A syncline plunging west-north-west forms a large lobe of Katangan units, mainly Kakontwe limestone, which dominates the centre of the field area. A smaller but similar lobe of Katangan units trending west-south-west occur to the south of the Lukanga River and along the Mulungushi River at Millberg.

Basement units outcrop mainly in the east and northeast of the field area. Their structural relationship is more complex than the Katangan units, although in the northeast a fairly well defined band of Muva schists and quartzites borders the Katangan units, and in the east central part of the area they form an anticline. Three main areas of granite gneiss have been mapped by the mining companies, in the northeast, in the east centre part of the area and in the south surrounding the Mulungashi River syncline of Katangan rocks.

Minor fracture systems trend north-north-west with a major fault running west-north-west through Mpongwe.

3.2.3 Mineralisation

There are seven known mineral occurrences in the Kadola area. These are for the most part copper showings occurring in the vicinity of the Lower and Upper Roan contact and are exemplified at Mwira and Kadola where disseminated stratiform copper occurs in the dolomite and sandstone of the Upper and Lower Roan (Fig. 6).

At Eureka, there is a stockwork of supergene enriched copper veins associated with Katangan rocks of unspecified age.

At Pyrite, massive pyrite occurs in Kakontwe limestone.

At Jack's Mine, copper mineralisation in the Lower Roan, and nickel in the form of garnierite, is associated with the serpentenite which outcrops there.

At Kashiba, a narrow chalcocite vein occurs in the Kakontwe dolomite.

At Millberg in the southeast of the field area, the only lead and zinc mineralisation occurs in sphalerite and galena in tabular shaped bodies associated with the Upper Roan dolomite.

In the east of the field area there are numerous copper drainage anomalies and to a lesser extent nickel associated with the Muva quartzites and schists.

3.2.4 Physiography and Drainage

Kadola area is bounded and drained in the north by the Kafulafuta River and in the south by the Lukanga River. Both these drain west to the Kafue River which runs south and bounds the west side of the area. Between these rivers the land is flat, particularly over the Katangan carbonate units in the centre and west; but it becomes more rolling in the east with 100 to 200 feet ridges and monadnocks above the general level formed by Basement and Lower Roan quartzites. This has resulted in the formation of broad flat dambos with very shallow hydromorphic soil development over the limestone, with apparently good internal drainage. Around the borders of these flat limestone areas the dambos become narrow, swampy and better defined; springs are common and develop into small streams in the dambos.

3.2.5 Climate

The climate is the same as that described for the provincial field area. The Kadola area lies between the 35 to 45 inch rainfall isoyhets.

3.2.6 Pedology

On a regional scale, most of the Kadola area falls within the ferrallitic soil zone; thus the description of the ferrallitic soil types in the provincial section applies in general to the Kadola soils. Soils on a local scale, however, are found to vary considerably over different lithologies.

Over carbonate and basic or ultrabasic rocks the well-drained, interfluve soils are dark red, sandy clays on the surface and increase with depth in clay proportions and darkness of colour. They do not have a well developed profile. They tend to be very variable in depth from a few inches to a few feet (Table 3(a)). In poorly drained areas they are brown or black without any profile and tend to be of a few inches in depth (Table 3(b)).

Over shales or schistose rocks, on the other hand, soils tend to be deep and have well developed horizons. The occurrence of thick horizons of laterite is used as an indicator of schistose rocks (Table 3(c)).

Over quartzites or sandstones the soils are usually white

Table 3

Soil Profiles over Different Lithologies in Kadola Field Area

(a) Soils over carbonate rocks in well drained areas

Location: Well drained soils over Kakontwe limestone near Kashiba Mine.

Depth	Horizon	Description
0-3"	A_1	Orangish red silty clay fine quartz sand, sometimes medium sand sized ilmenite is concentrated on the soil surface; blocky angular structure; hard when dry; gradational boundary.
3"-18"	B_1	Dark orangish red silty fine sandy clay; angular blocky structure; hard when dry; sharp boundary.
<18"	Bedrock	Massive impermeable marble.

(b) Soils over carbonate rock in poorly drained areas

Location: South of Kadola Mine on Kakontwe limestone.

Depth	Horizon	Description
0-3"	A_1	Brownish grey fine sandy clay; blocky angular structure; hard when dry; gradational boundary.
3"-15"	B_1	Dark brown fine sandy clay; blocky angular structure; hard when dry; laterite pellets increase with depth.
15" and below		Massive laterite or bedrock massive impermeable marble.

Table 3 (cont.)

Soil Profiles over Different Lithologies in Kadola Field Area

(c) Soils over Schists

Location: South of Mpongwe from pit over Katangan schist.

Depth	Horizon	Description
0-3"	Ao	Grey silty fine quartz sand; structureless; friable when wet; with little organic matter; gradational boundary.
3"-6"	A2	Yellow rusty silty fine quartz sand; structureless; friable when wet; gradational boundary.
6"-2'	B1	Yellow silty clayey fine quartz sand; weak blocky fine structure; soft when moist; gradational boundary.
2'-4'	B1	Rusty yellowish red silty, clay fine quartz sand with iron laterite pellets up to ½" in diameter increasing in concentration with depth; weak fine blocky structure; soft when moist; gradational boundary with laterite pellets increasing in density until they form conglomerates of pellets.
4'-9'	B2	Massive dark red laterite with minor quartz and pebble content formed of conglomerate of laterite pellets; sharp boundary.
9'-11'	C1	Red and grey mottled silty fine quartz sandy clay; blocky angular structure; gradational boundary.
11'-15'	C2	Red mottled grey soft weathered clayey schist.

quartz rich, particularly in the upper leached horizons, and tend to be a rusty colour after about one foot (Table 3(d)).

Over granites the soils tend to be deep and well developed. The top horizon tends to be white and highly siliceous. The clay content increases and colour becomes a light, rusty yellow with depth (Table 3(e)).

3.2.7 Drainage sediment

As with the soils, drainage sediment is controlled by lithology and can be divided into two basic types:

(a) dambos draining carbonate and ultrabasic rocks, and

(b) normal dambos draining other lithologies.

The latter drainage sediments have already been described in the section on provincial drainage sediments. It is only necessary to remark that there are a number of dambos with swamp areas, and owing to the rapid helicopter sampling programme used in the initial reconnaissance, it is likely that a number of organic rich samples were taken.

Drainage sediments overlying carbonate and ultrabasic rocks are black or brownish black clays of a few inches or more in depth and underlain by the bedrock. There is no profile development as such. Pellets of iron and manganese form in these soils and are often concentrated in a surface layer by eluviation of the finer fractions. In some places they have become cemented into a conglomerate mass of pellets. At seepage springs draining carbonate rocks, swamps tend to develop and the sediment is very fine black clay with often much organic material and white calcrete blebs.

Table 3 (cont.)

Soil Profiles over Different Lithologies in Kadola Field Area

(d) Soils over quartzite

Location: Over Muva quartzites in east of field area.

Depth	Horizon	Description
0-9"	A	White or creamy white quartz sand; structureless; friable when wet; gradational boundary.
9"-24"	B1	Light rusty orange silty quartz sand; structureless; friable when wet; gradational boundary.
24" and below	C	Quartz pebbles prevent further augering.

(e) Soils over granites

Location: Over southern acid crystalline outcrop near Millberg.

Depth	Horizon	Description
0-6"	A1	Light grey silty coarse quartz sand; structureless; friable when wet; gradational boundary.
6"-15"	A2	White silty coarse quartz sand; structureless; friable when wet; gradational boundary.
15"-60"	B1	Light rusty white silty coarse quartz sand.

3.2.8 Geochemistry

Roan Selection Trust sampled the Kadola area on the basis of one sample every mile along the drainage channels. These were analysed chromatographically for Co, Cu, Ni, Pb and Zn. The results have been evaluated by the company geologists on the basis of selection of anomalies possibly resulting from mineralisation. Interpretation of the data on a regional basis indicated a general increase in element level in the east and northeast of the field area. Apart from relating this increase to higher background values in the Basement compared to Katangan lithologies, little other information concerning the geology could be interpreted from the data (Wilding, I.G.P., pers. comm.).

3.3 LUSAKA EAST AREA

3.3.1 Geology

Lusaka East area lies along the Great East Road east of longitude 28°30' (Fig. 1). Basement rocks underly most of the area, with the exception of some Karroo sediments in extensions of the downwarped rift valleys, and a schistose area in the southwest of the area which has been correlated with Mwashia Group of the Katangan System. Outcrop is relatively good over the area, which has resulted in reasonably accurate lithologic maps originally compiled from the Mineral Concession Geologists' work, with additions by Chartered Exploration and the Geological Survey (Fig. 7).

Most of the southwest of the area is underlain by granite gneiss, and the northeast and extreme east of the area by schistose rocks in association with quartzites with minor bodies of granite. Basic rocks composed of amphibolites and metavolcanics, referred to

Fig: 7 Generalised geology of Lusaka East area.

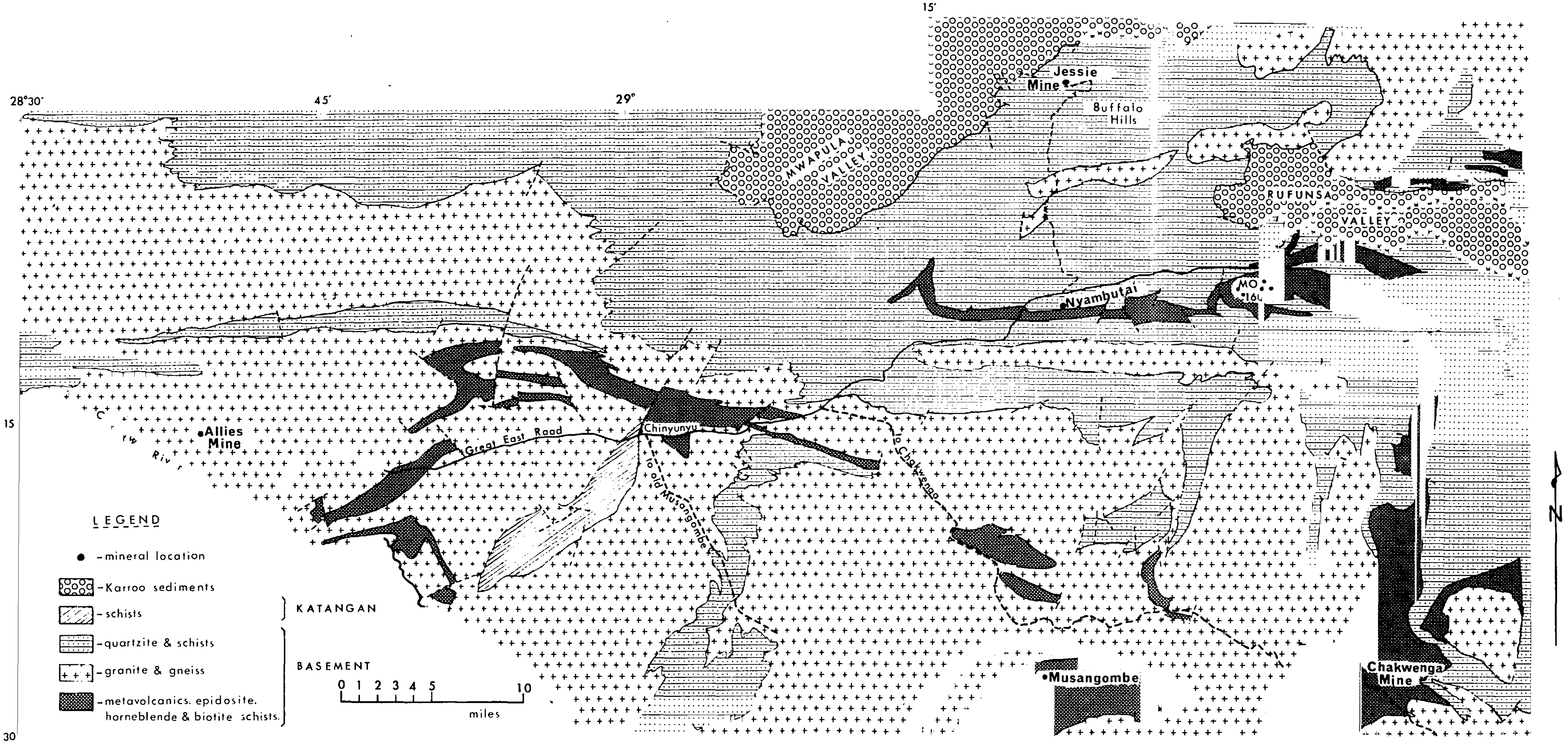

Fig: 7 Generalised geology of Lusaka East area.

as the Rufunsa volcanics, outcrop in fairly well-defined belts parallel to the general trend. The divisions of Basement units on the geological map are largely lithologic, due to the difficulties of defining the stratigraphy across the structural complexities and high grade metamorphism.

Granite and granite gneiss is variable in composition with different proportions of accessory minerals such as muscovite, biotite and some hornblende. The feldspars are variable in composition.

A progressive increase in metamorphic grade is suggested by the increased degree of granitisation of rocks to the south, other than metavolcanics and quartzites, and by the more abundant ungranitised pelitic schists to the north, which ultimately grade into ungranitised, high grade metamorphic pelitic schists in the northeast (Simpson, 1967). All the granite gneiss has a strong foliation, and much of it a blastomylonitic texture. Most of the granites and granite gneisses are thought to be formed largely by granitisation of metasedimentary pelites, semipelites, and psammites previously folded. These were largley refoliated during the main phase of the Lufilian orogency forming flaser and augen gneiss; some banded gneisses were transformed to quartz mica schists.

Schists in the field area have been divided into three basic types: phyllonitic schists, psammitic and pelitic schists. Their distribution has only been clearly defined over the central part of the field area (1529 NW quarter sheets) mapped by Simpson (1967), but a knowledge of the origin of the different schists is important for an interpretation of minor element backgrounds, if the minor element content reflects the original rather than the present rock type.

Phyllonitic schists are sheared granite gneisses in which the feldspars become muscovites.

Psammitic schists are quartzose, muscovite and biotite schists, which occur in the north of the area and grade to pelitic schists in the northwest, interrelated with thin quartzite horizons. Garnet-staurolite schists occur in the northern central Mwapula area and disseminated graphite is common in these schists.

The Rufunsa volcanics outcrop in two well-defined belts. With the exception of the large area around Musangombe mine, which is believed to be intrusive, they are extrusive volcanic rocks of essentially basaltic composition. They range, however, from possible andesites to olivine basalts in original composition, and some appear to have had microcline introduced, particularly those that occur in the southeast of the area. Vesicules filled with quartz and epidote occur in many of the rocks. These volcanics now usually outcrop as a massive, fine grainted, hard, resistant 'epidosite' composed of epidote and quartz; however, these are probably unrepresentative of most of the volcanics, which are composed of amphibolites with combinations of quartz, epidote and albite; quartz and plagioclase; garnet, plagioclase and quartz, and various types produced by retrograde metamorphism in which biotite and chlorite are the dominant mafic minerals (Simpson, 1967).

The quartzites in the field area form ridges 200 to 500 feet above the general level. They are relatively pure quartzite with minor amounts of mica and limited sedimentary structures which suggest their sedimentary origin. Some quartzites contain tourmaline.

Schists, believed to be of Katangan age, outcrop to the southwest of the field area, and some graphitic and apparently younger schists in Jessie Mine area have been correlated with them by Simpson (op. cit.). They are composed of garnet muscovite and chlorite in the south west, and biotite, quartz with muscovite, chlorite and a few small garnets with interbedded graphitic calcareous bands in the north.

Karroo sediments occur in the downwarped Mwapula valley to the north and Rufunsa valley to the east. Samples were not taken from these areas.

A few small basic intrusions occur mostly as plugs with some dyke-like forms. They vary from medium-grained dolerites to coarse-grained gabbros.

3.3.2 Structure

Orogenic folding and granitisation resulted in stratigraphic discontinuity of the Basement prior to the onset of the Lufilian deformation. Relic structures from pre-lufilian orogenies, however, have not been recognised in the area owing to the all-pervasive Lufilian structures.

The dominant foliation, which varies from WNW to WSW is a result of refoliation of the Basement by the intense early Lufilian deformation in a northwesterly direction. This foliation direction has been modified by the strong shearing along the Mwembeshi and Zambezi zones of dislocation (Fig. 2) and a further stress with maximum pressure on an axis slightly west of N, due to convergence of these two zones. This has resulted in the NNE trending foliation in the southeast of the field area, and a general WNW to WSW trend elsewhere. Further folding of broad open folds on northeast axis took place to a minor extent in the area west of Jessie Mine road (op. cit.).

Faults are related to the major shear zones, but their movement sense cannot be worked out in detail.

Except for the rifts, post-Lufilian structures are insignificant.

3.3.3 Mineralisation

Mineral occurrences of gold, copper, iron, bismuth and tourmaline are known in Lusaka East area, but only gold and copper are present in significant amounts.

The more interesting copper mineralisation occurs along ferruginous and biotite rich shear zones, usually in the form of malachite or chrysocolla encrustations along the shear planes; primary sulphide mineralisation is rarely present. The main known deposits of this kind are Allies Mine in the west, Musangombe Mine in the southern central part of the area, and at Kalulu showing in the extreme southeast corner east of Chisangombe Mine.

In the northeast, copper mineralisation, again in the form of malachite and chrysocolla, occurs in apparent association with the quartzite ridges, either as malachite veinlets in joints or fractures in the quartzite, or in the fine-grained black phyllite. The best examples of this type of occurrence is found at Buffalo Hills and Nyambutai prospects.

Copper mineralisation, in the form of malachite, chalcopyrite, bornite and chalcocite, occurs as small pockets within the metavolcanics or associated with small, irregular cross-cutting quartz veins. Mineralisation of this type occurs in the east, at M0160, just south of the Great East Road.

Gold, sometimes associated with copper, occurs in quartz veins. The main occurrences are at Jessie Mine and in the south at Chakwenga Mine, but it is also associated with the copper at M0160.

3.3.4 Physiography and drainage

Lusaka East lies just north of the Zambezi escarpment. In the west and central part of Lusaka East the topography is relatively flat since it is still part of the main plateau. Quartzite ridges up to 300 and 500 feet above the general plateau level follow the general structural trends, and tend,however,to break up the monotony of the plateau. The topography falls away in a series of incised, steep banked valleys in the south towards the Zambezi escarpment, the east towards the Rufunsa valley and north towards the Lunsemfwa and Mwapula valleys.

Drainage courses are dendritic on the flatter dambo areas, but tend to be controlled by structural alignments and faults in the more incised areas. Dambos are the main drainage type on the plateau, but vary between dambo and streams in more rugged areas towards the escarpment.

3.3.5 Climate

Climate is as described in the provincial section with the area lying between the 35 to 25 inch rainfall isoyhet.

3.3.6 Pedology

The soil types vary locally depending on the combined factors of relief and geology. In general, the soils are much shallower than those in Kadola area to the north. Lithosols occur wherever the terrain is steep, either on the quartzite ridges or on the escarpments areas. The character of lithosols have already been described in the description of the provincial area. Elsewhere on the plateau the soils are light red, and sandy, with the clay and mica content varying with the underlying bedrocks of quartzite, schists and granitic rocks. Red clays which grade into dark brown to black clays in poorly drained areas occur over the basic volcanics.

3.3.7 Drainage sediment

Drainage sediment varies with the topography and geology like the soils. On the plateau, characteristic grey, clayey dambo sediments occur, which become black over the basic rocks. Dambos also occur between the steep quartzite ridges but are often complicated by deep A_0 vegetation horizons in areas of blocked drainage around seeps. Upstream above a seep, these organic rich sediments can often be replaced in a short distance by a sand sediment typical of escarpment streams. Yellow sands are typical of the incised escarpment streams to the east, and northeast and extreme south.

3.3.8 Geochemistry

Drainage sediment in Lusaka East area was sampled on the basis of one sample every ¼ to ½ mile along the dambo and stream channels by Chartered Exploration. This has resulted in a close sample coverage over much of the area because of the high stream density especially in the incised areas. Where dambos are the dominant drainage, the sample density is considerably reduced. The samples have been analysed for Co, Cu, Ni, Pb and Zn colorimetrically. Anomalies have been selected and evaluated on the basis of possible associated mineralisation. The plotted results were contoured by hand, in order to define any trends of mineralisation or regional trends of the geology. Owing to the high variance of the data this was extremely difficult and time consuming. The results showed a general correspondence of high Co, Cu, Ni and Zn values with areas of known occurrences of basic rocks. Lead showed insignificant variation as most of the samples were below detection limit for lead. Although it was possible to show the above correspondence it was a difficult and imprecise procedure involving the superposition of four element maps and the geology map. No other meaningful trends or associations were noted.

CHAPTER 4

FIELD SAMPLING, SAMPLE PREPARATION, ANALYTICAL TECHNIQUES AND DATA HANDLING

4.1 INTRODUCTION

Field work was carried out during the dry seasons in 1967 and 1968. During the first field season drainage samples were taken over the 80,000 square miles of the provincial reconnaissance field area and the samples were prepared and analysed in Zambia by atomic absorption for Cu, Co, Ni, Pb and Zn. Subsequently, they were analysed spectrographically for 16 elements at the Applied Geochemistry Research Group.

Samples from the Lusaka East and Kadola areas were selected from the regional drainage sediment reconnaissance samples already collected by Chartered Exploration and Roan Selection Trust. These samples, which had already been prepared for analysis, were analysed in the same way as the provincial samples.

The analytical results were plotted and interpreted with the aid of the computational techniques at Imperial College.

During the second field season in 1968 rock, soil and duplicate and additional drainage sediment samples were taken over a selection of the most significant minor element patterns revealed by the initial drainage samples in order to investigate the relation of the geochemistry of drainage sediment to primary and secondary geochemistry.

Samples collected during the second field season in the areas of interest were all prepared and analysed in Lusaka in Chartered Exploration laboratories by atomic absorption and spectrographic methods. The minor element content of samples, which had to be compared, were always analysed by the same method, and usually in the same batch, to avoid spurious variations due to changes in level of values between different methods of analysis and between different batches using the same method.

4.2 FIELD SAMPLING

4.2.1 Provincial drainage sediment sampling

The broad scale drainage sediment reconnaissance sampling over 80,000 square miles of central Zambia was carried out at a nominal density of one sample every 50-100 square miles (Fig. 8). The sample locations were largely limited to points where motorable roads crossed or came close to drainages. Most of the sampled drainages had catchments upstream from the sample point of below 10 square miles. On the plateau the drainages sampled were mostly small dambos, sometimes with a well defined drainage channel, and in the escarpment areas they were mostly small steep-banked streams. Samples were also taken from large drainages, up to 100 square miles in catchment area, in order to test the extent to which large catchments reflect the local primary geochemistry.

Dambo sediment samples were taken from the upper G_1, grey, clayey-sand or sandy-clay horizon, below the A_0 organic horizon and above the pale coloured leached horizon, using a mattock or hand auger. The depth of this type of sample varied but was usually from 1 to 9 inches (Table 2(d)). In dambos with a thickly developed organic horizon, which occur particularly in the wetter northern half of the field area, the G_1 horizon might occur at 3 feet in depth. In streams on the plateau and stream channels through dambos, the sediment

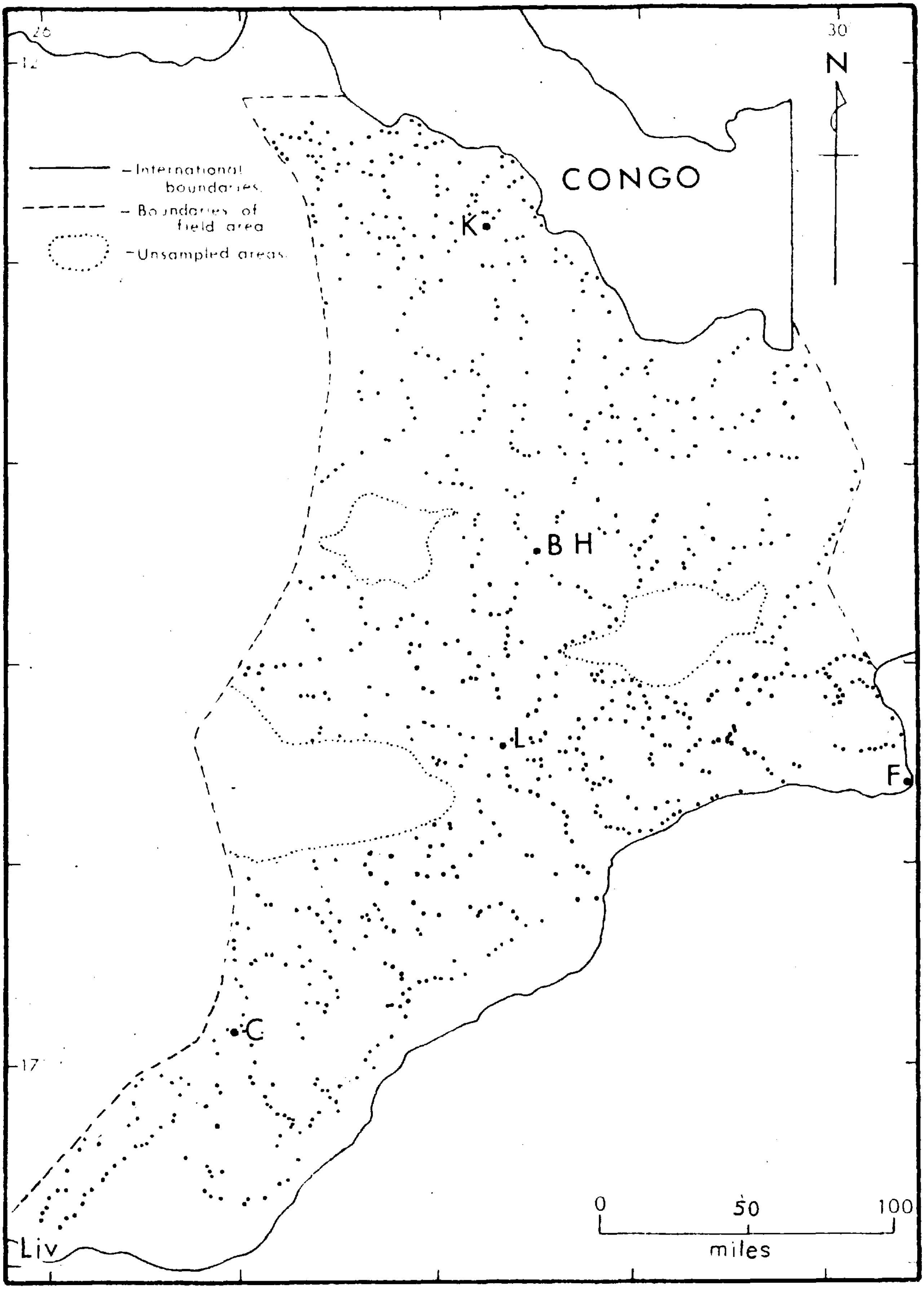

Fig: 8 Drainage sediment sample location plan of provincial reconnaissance survey.

consisted of grey sandy clay or clayey sand and was essentially similar in appearance to the dambo sediment. Care was taken to avoid organic material and coarse sediment from which the clay fraction had been washed away by running water.

In drainages in the escarpment areas the stream sediment samples tended to be rusty-coloured sand. Samples were taken from wherever the finer sediment had tended to accumulate.

In order to reduce sampling error, half of each sample was taken from two points from 50-100 feet apart at each location. Duplicate samples were taken from each location, and the sediment taken in small (3 x 5 inches holding about 300 gms) and large (5 x 10 inches holding about 1 kilogram) kraft paper bags. The pH of drainage water was taken wherever water was available, using British Drug Houses 'Universal' pH indicator. The catchment size was calculated from the 1:50,000 Ordnance Survey map sheets for the small drainages and the 1:250,000 scale maps for the large drainages. Samples were always taken well upstream from roads in order to avoid contamination; drainages with known mineralisation or mine contamination were not sampled. Maps were made available by Roan Selection Trust and Zambian Anglo Mine Services showing these locations in the Copperbelt mining area, and by Chartered Exploration in the Broken Hill and Lusaka East areas.

The total area sampled was about 80,000 square miles with 1,100 drainage samples, giving an overall average of one sample every 73 square miles. It was attempted to maintain as even a network of sample points as possible, but this was not always feasible in areas with poor access and/or poor drainage density.

4.2.2 Regional drainage sediment sampling in Kadola and Lusaka East areas

The initial drainage sediment reconnaissance samples from Kadola and Lusaka East areas were collected during routine mineral exploration of these areas by Roan Selection Trust and Chartered Exploration, respectively. The samples in Kadola area were taken at 1 mile intervals along the drainages. This has given an average cover of approximately one sample every 2 square miles. In Lusaka East area the drainage was sampled at ¼ to ½ mile intervals. Samples were selected from this very dense sampling to give one sample every 2 square miles in order to make the results more comparable with the Kadola area and to provide a manageable number of samples for analysis. Notes on the type of sediment and secondary environmental conditions at the individual sample sites were not available.

In Kadola area a helicopter was used to carry out the sampling programme. The actual sampling had to be carried out very rapidly using a mattock, with little time to select a consistently similar drainage sediment type at each location. This is likely to have resulted in sample types varying from organic rich dambo sediments, to the normal grey sandy clay dambo sediment, with the latter being the more frequent type, since that is the dominant drainage sediment in the area (Wainwright, pers. comm.).

In Lusaka East area sampling was done by landrover or on foot. In theory, this might have led to a more consistent sample type, since more time could be given to the choice of a sample; in practice, however, divergence of sampled sediment is likely to be greater because of the differences of drainage sediment type occurring in Lusaka East area. The sediment samples are likely to vary mainly between the sand samples in the streams and the ordinary grey clays in the dambos with some organic rich dambo samples.

4.2.3 Soil Sampling

Soil sampling during the second field season was carried out at a comparatively regular interval along the roads which traversed a selection of the element patterns defined by the minor element content and factor R-score patterns from the drainage sediment samples. Owing firstly to the poorer representativity of soils compared to drainage samples, which would tend to be more of a composite of the minor element content of rocks in the upstream catchment area, and owing secondly to the lack of time and access to take samples on a two dimensional grid, soil samples were taken at relatively close intervals. Care was taken in both the provincial and regional surveys, that there was an adequate number of soil samples, over any one pattern, to define the geochemistry.

The soil samples were taken with a hand auger from the top of the B horizon as it is termed by agriculture soil scientists (Zambia Department of Agriculture, 1965) or the A_2 as termed by geochemists (Jay, 1959). This horizon varies from 6 inches to 4 feet, averaging about 2 feet in depth and is recognised as being slightly darker than the leached overlying A horizon. It occurs above the laterite horizon through which it was impossible to drive a hand auger. The soil was collected in kraft paper bags in the same way as the drainage samples, and half of each sample was taken from two auger holes about 50-100 feet apart at each sample location.

4.2.4 Bedrock sampling

Rock samples were taken wherever outcrops occurred along the traverse routes and appeared generally representative of bedrock geology shown on the available geological maps (Reeve, 1963; de Swardt et al, 1964). Rock samples were also obtained from the collection at the

Geological Survey of Zambia in order to supplement the number of samples in areas of poor outcrop, which occurred particularly in the north of the field area.

Rocks were sampled by taking a number of representative chip samples from an outcrop to a total of about 2-3 kilograms. Where two or more rock types occurred in the same outcrop, samples were taken of each rock type. Rock samples from the Geological Survey collection were of necessity much smaller, usually about half of a normal hand specimen.

4.3 SAMPLE PREPARATION

4.3.1 Drainage and soil samples

The optimum methods of sample preparation developed by previous workers in Zambia (Hawkes and Webb, 1962), have been used for all the soil and drainage samples throughout this study.

Drainage and soil samples were sun-dried in the field in the sample envelopes. One of the samples from each site was lightly crushed in a mortar and pestle to break up aggregates of silt and clay and sieved through 80-mesh nylon bolting cloth in a perspex sieve. All analyses were carried out on this minus 80-mesh fraction. The duplicate sample was retained for reference purposes.

4.3.2 Rock samples

Rock samples were crushed in a jaw-crusher to ½ to ¼ inch fragments and quartered in a splitter. Three-quarters of the sample was kept for reference and the remainder pulverised to about minus 80-mesh in a tungsten carbide steel disc mill. Resistant grains and mica flakes were usually much coarser than minus 80-mesh and the sample was again quartered in a splitter and a ¼ of the sample crushed in a porcelain ball mill to approximately minus 200-mesh Five samples were pulverised with an agate mortar and pestle, in addition to the above method, after the jaw crushing stage, to check for any contamination from the disc crusher and porcelain ball mill. Results of analyses from the optical spectrograph and mass spectrograph at the Australian National University have shown that the only significant contamination from a tungsten carbide mill is cobalt and tungsten (A.P. Capp, pers. comm.). A comparison of cobalt values in samples crushed in the agate mortar and pestle and those crushed in the tungsten carbide disc mill and porcelain ball mill show only a little increase of cobalt in four out of the five samples prepared by the latter method, which is well within the analytical precision (Table 4). The other elements showed no consistent or significant variation.

Table 4: Comparison of cobalt analyses of rock samples crushed by tungsten carbide disc mill and samples crushed by agate mortar and pestle.

Sample No.	Disc pulveriser and procelain ball mill	Agate mortar and pestle
8110	40 ppm	35 ppm
8111	35	30
8112	25	20
8114	40	30
8116	20	20

4.4 ANALYTICAL METHODS

4.4.1 Introduction

All the analyses were carried out by atomic absorption and/or emission spectrography.

The drainage samples taken during the first field season were analysed for Co, Cu, Ni, Pb and Zn by atomic absorption by Chartered Exploration laboratories in Lusaka, and for Ag, Bi, Co, Cr, Cu, Fe_2O_3, Ga, Mo, Mn, Ni, Pb, Sn, Sr, Ti, V and Zn by emission spectrography at the Applied Geochemistry Research Group (A.G.R.G.). The rock, soil and additional drainage samples taken during the second field season were all analysed in Lusaka at the Chartered Exploration (C.E.) laboratories for Co, Cu, Ni and Zn by atomic absorption and for Cr, Ga, Mn, Pb, Ti and V by emission spectrography.

The analytical techniques used in this project were developed for the rapid routine analysis of geochemical samples. Accuracy, precision have to some extent been sacrificed in order to analyse a large number of samples. In the context of routine mineral exploration such as is carried out by Chartered Exploration where contrasts between background sample values and anomalous sample values derived from mineralisation are expected to be high, these semi-quantitative methods are quite adequate. The sensitivity of the C.E. analytical methods particularly at the low background level for most of the elements was poor. The A.G.R.G. analytical methods, which have been used to develop rapid geochemical analytical techniques and geochemical reconnaissance methods are somewhat more sensitive at the low element levels and more accurate, although the precisions of the two laboratories were found to be comparable.

It is one of the objectives of this project to show that, without adding excessively to the analytical requirements of these established techniques, further useful information can be gained concerning the geology which might aid mineral exploration by interpreting the variations of background concentrations.

In the context of geochemical sampling where the sampling representativity is generally poor, it is important to have a relatively large number of samples in order to define regional or provincial trends. It is important, therefore, to have a rapid analytical technique, even if this necessitates some reduction in accuracy or precision.

In general, the analytical techniques developed for mineral exploration were adequate for the purpose of defining regional trends of background values, except when discrimination and sensitivity were poor in the background range of values. Element analyses which had these inadequacies will be discussed in the following sections.

4.4.2 Atomic Absorption

All the atomic absorption analyses were carried out by the Chartered Exploration laboratory in Lusaka. Their method utilises 1½ ml. of concentrated nitric-perchloric acid attack with 2:1 HNO_3:$HClO_4$ ratio on 0.2 gm. of sample. This is boiled for half an hour, and diluted to 10 ml. with deionized water. The solution is then sprayed on a Perkin-Elmer atomic absorption unit with the appropriate lamp for each element. A Tektron instrument was used for the zinc analyses in 1968.

Initially the method had a poor sensitivity in the 20 to 40 ppm range of all elements, and most samples with values of below

40 ppm were read as 20 ppm. This resulted in truncated frequency distributions on which it was difficult to use statistical methods meaningfully. The analyses of the samples during the first field season have not been used for this reason except as a rough check on the spectrographic analyses for the same elements.

The sensitivity of this atomic absorption method for samples analysed during the second field season, however, was considerably improved, with a lower detection limit of 5 ppm for Co, Cu and Ni and 2 ppm for Zn. Lead was not analysed by this method because the sensitivity could not be improved below 20 ppm and the majority of samples were below or in the region of 20 ppm. Precision was analysed using statistical control samples and duplicate analyses and will be discussed later.

4.4.3 Spectrographic analysis at the Applied Geochemistry Research Group

The technique for the multi-element analysis of geochemical samples using the emission spectrograph has been developed at the Applied Geochemistry Research Group and is described by Nichol and Henderson-Hamilton (1965) following the work of Kerbyson (1960) and Chartered Exploration at Lusaka.

The method utilises a lithium carbonate buffer in order to minimise the effects of different matrix compositions and 300 ppm of germanium as an internal standard in order to check the quality of the burn. The lines are recorded on photographic plates and read against a standard plate.

The original analyses included Ag, Bi, Co, Cr, Cu, Fe_2O_3, Ga, Mn, Mo, Ni, Pb, Sn, Sr, Ti, V and Zn. Ag, Bi and Mo values, however, were mostly below the detection limit and were not used in the subsequent interpretation.

All values are quoted in ppm except iron which is expressed as percentage of ferric iron . It should be noted that the emission-spectrograph measures total iron in the sample and not just ferric iron . The result is simply quoted in terms of ferric iron.

4.4.4 Spectrographic analysis at Chartered Exploration

The spectrograph at Chartered Exploration was used for analysing all the samples taken during the second field season for Cr, Ga, Mn, Pb, Ti and V. The main differences from the A.G.R.G. emission spectrographic method was that no germanium internal standard was used, the lines were recorded on film rather than plates and no buffer was used to reduce matrix effects. The only buffer available was carbon and twenty rock samples of differing composition were analysed with and without 5 parts carbon buffer to 1 part sample. Within the precision of the method the level of results were comparable. Owing to the large proportion of buffer required, however, the sensitivity was decreased to such an extent that any usefulness in greater precision gained was negated. The buffer was not used, therefore, in subsequent analyses.

4.4.5 Analytical Accuracy

If any comparisons of element level are to be made with other geochemical surveys some measure of the analytical accuracy is imperative. For this reason, a selection of samples from all the different methods were re-analysed, with standard G_1 and W_1 rock sample material as control with each plate, on the A.G.R.G. spectrograph. Mean and standard deviation ranges of the various elements for 39 and 40 analyses of G_1 and W_1 samples, respectively, are shown in table 5 with the accepted values from Fleischer and Stevens (1962) for comparison.

With some exceptions the accuracy (a) for most of the elements analysed on the A.G.R.G. spectrograph is good. The exceptions are cobalt which tends to be 50% higher than the accepted values for W_1, (b) manganese which tends to be 40% lower than accepted G_1 values but are close to the accepted W_1 values, (c) nickel which tends to be 40% higher than the accepted W_1 value, (d) strontium which tends to be 40% and 20% lower than the G_1 and W_1 values, respectively, and (e) vanadium which tends to be 20% and 50% higher than the accepted G_1 and W_1 values, respectively. These results indicate the general accuracy of the A.G.R.G. spectrograph during the latter part of 1968.

In order to have a measure of the accuracy of the data analysed on the A.G.R.G. spectrograph during 1967, and at Chartered Exploration during 1968, minor element values from a random selection of the samples which had been analysed with G_1 and W_1 were plotted on graphs against the original values (Figs. 9 and 10). Analyses carried out with the G_1, W_1 control samples have been plotted on the Y-coordinate and the other analyses along the X-coordinate. In Fig. 9 the analyses on the X-coordinate are from the A.G.R.G. spectrograph of drainage samples taken during the first field season. From the graphs it can be seen that there is a relatively good correlation for most of the elements along the 45° line. The main exception is vanadium which tends to be about

	G_1		W_1	
	Values from AGRG Spectrograph	Values from Fleischer &Stevens	Values from AGRG Spectrograph	Values from Fleischer & Stevens
Co	67% values <5 ppm det. limit	2 ppm	81 ppm 69-94	52 ppm
Cu	15 11-20	13	113 80-158	110
Cr	16 10-24	22	142 111-182	120
Ga	22 16-31	18	16 13-220	16
Fe_2O_3	1.6% 1.4-1.8	1.58%	10.9% 8.9-13.4	10.8%
Mn	143 114-180	230	1385 1207-1589	1320
Ni	54%=5ppm det. limit 46% <5ppm	1-2	114 85-153	80
Pb	51 43-60	49	5 4-8	8
Sn	71%<5ppm det. limit	2-3	0 samples >5ppm det. limit	2-3
Sr	168 110-250	250-280	170 113-257	220
Ti	1380 983-1940	1500	7325 5822-9217	6400
V	28 22-35	16	368 291-465	240
Zn	48 37-62	40	83 52-132	82
No. of analyses	39		40	

Table 5: Geometric mean and single standard deviation ranges of G_1 and W_1 average values analysed on AGRG emission spectrograph compared with accepted values (Fleischer and Stevens, 1962).

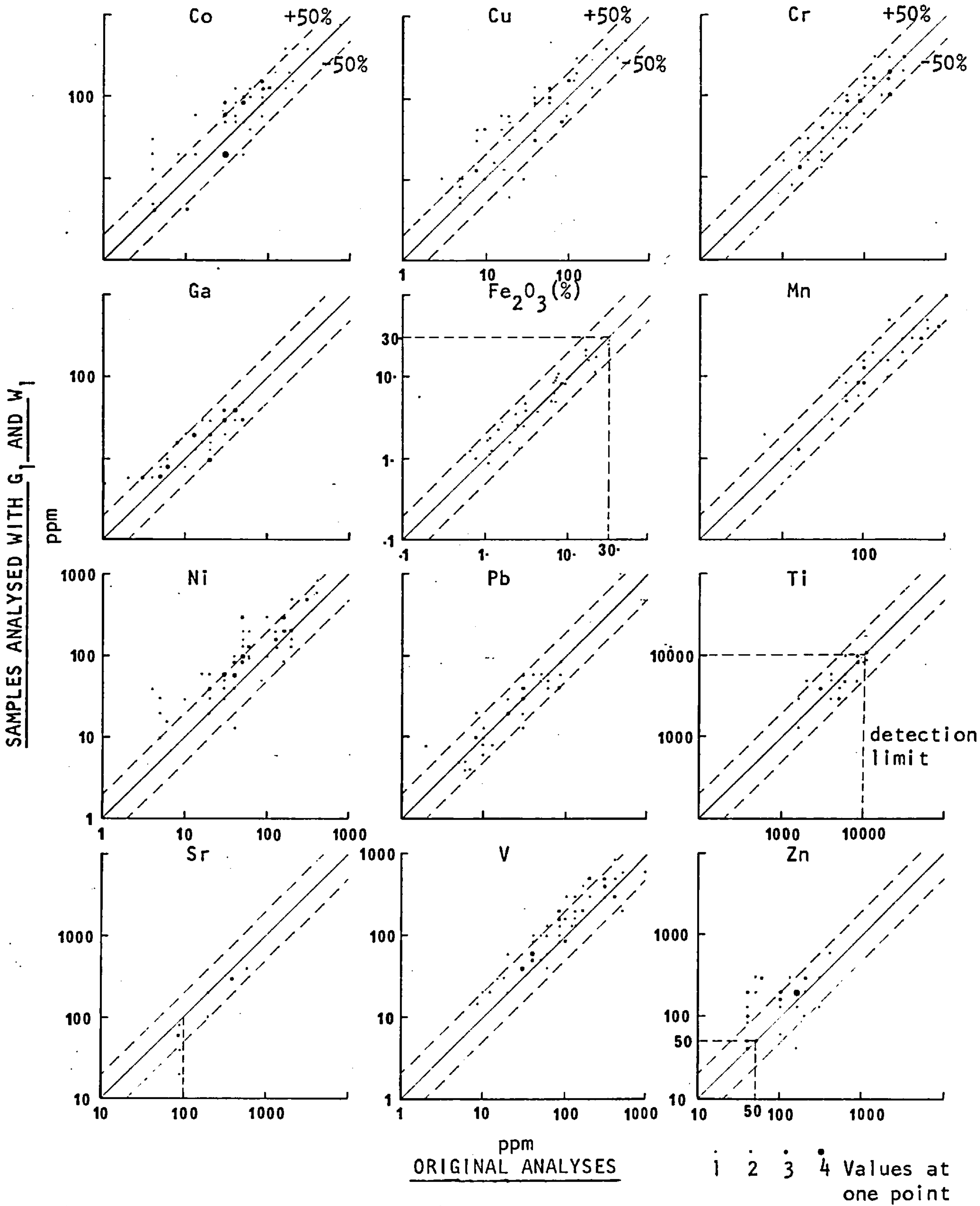

Fig: 9 Original A.G.R.G. emission spectrograph results compared with values of same samples analysed with G_1 and W_1
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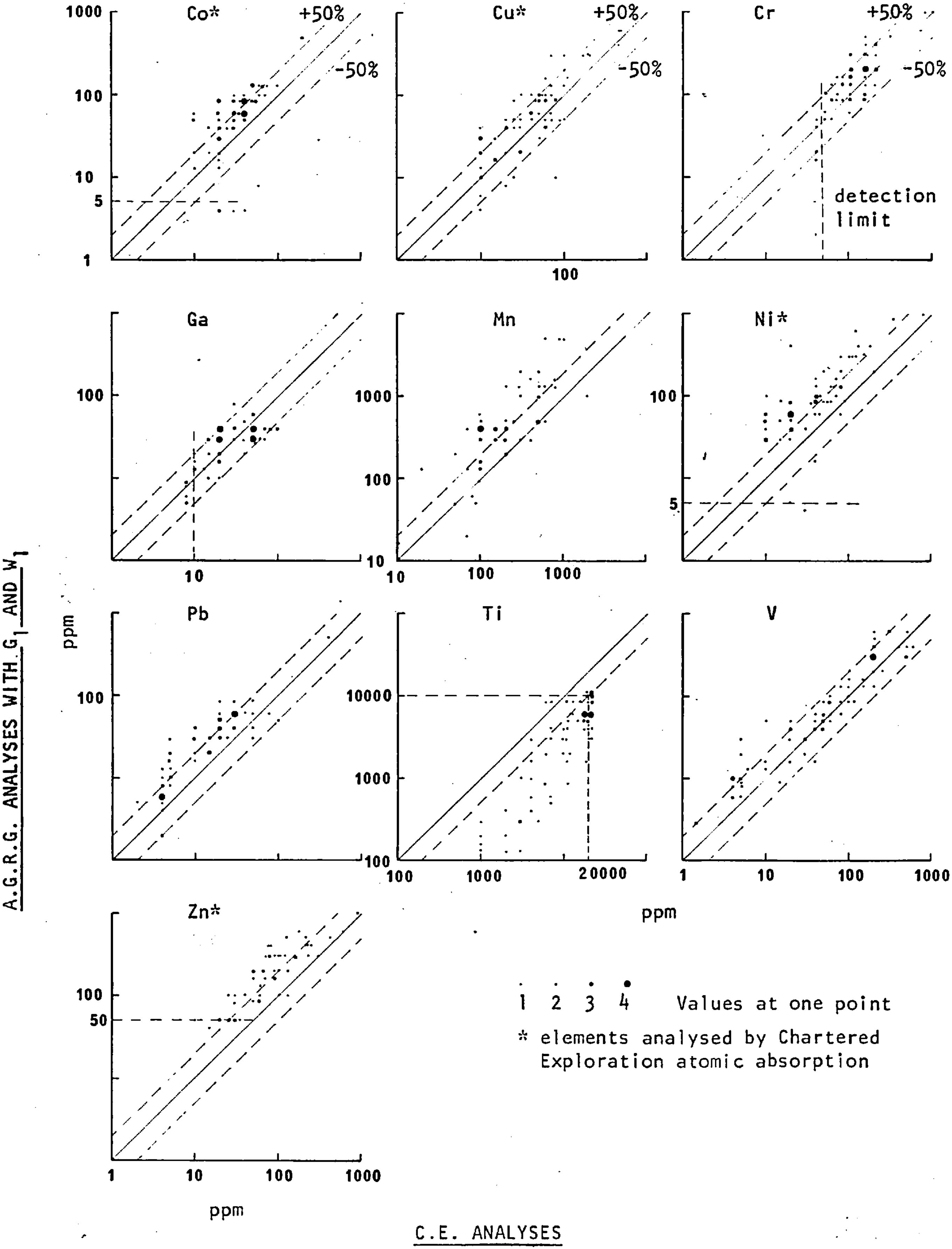

Fig: 10 Chartered Exploration atomic absorption and emission spectrographic values compared with values of the same samples analysed with G_1 and W_1 on the A.G.R.G. emission spectrograph

25% greater during the second analyses with G_1 and W_1 control samples. Since the G_1, W_1 values for vanadium were about 70% and 50% too high respectively, there is a suggestion that the original analyses were more accurate than the check analyses but still about 45% and 25% above the real value at the low and high values, respectively. Other elements would diverge from the "true" value by the amount that the G_1 and W_1 values diverge from accepted values already noted.

In Fig. 10 the values plotted on the X-axis are those from Chartered Exploration atomic absorption. In Fig. 10 the analyses on the Y-coordinate are those from Chartered Exploration atomic absorption and spectrograph of the rock, soil and drainage samples taken during the second field season. The graphs show that results from Chartered Exploration give relatively good linear correlation with values from the A.G.R.G. spectrograph, although the values for some of the elements are at somewhat different levels. For example: (a) cobalt results from atomic absorption are about 50% lower on average than the A.G.R.G. spectrograph. Since W_1 values are about 50% greater on average than the accepted cobalt values, the atomic absorption results are probably more accurate than the A.G.R.G. spectrograph results; (b) copper values from the atomic absorption are about 25% lower on average than those from the A.G.R.G. spectrograph. Since the G_1, W_1 mean values for copper on the A.G.R.G. spectrograph are very close to accepted values, the C.E. atomic absorption results are therefore considered to be about 25% below "true" value; (c) chromium values from the C.E. spectrograph show correlation with the A.G.R.G. spectrographic results. However, the sensitivity or discrimination below the 100 ppm level of the C.E. spectrograph is poor, with a lower detection limit of only 50 ppm. Above about 200 ppm, C.E. spectrographic values tend to be about 50% lower than A.G.R.G. spectrographic values and are therefore considered to be about 50% lower than the "true" value, since the mean G_1, W_1 chromium values from the A.G.R.G. spectrograph are relatively close to the accepted values; (d) gallium results from both spectrographic methods give a good correlation and appear to be reasonably accurate; (e) manganese values obtained on the C.E. spectrograph are about 50% below A.G.R.G. values in the 100 to 500 ppm range and about 70% below A.G.R.G. values in the 1000 ppm range. Since G_1 values from the A.G.R.G. spectrograph are also about 40% lower than accepted values, the C.E. spectrographic results are probably about 90% below the "true" value in the 100-500 ppm range and about 70% below in the 1000 ppm range; (f) nickel values from the C.E. atomic absorption results show a good correlation with the A.G.R.G. spectrographic results, although they are on average about 60% lower. Since the mean W_1 values from the A.G.R.G. spectrographic analyses are about 40% higher than the accepted value, it would appear that the C.E. atomic absorption results are about 20% lower than the "true" value; (g) lead values obtained on the C.E. spectrograph tend to be about 50% lower value than A.G.R.G. spectrographic values, that is to say about 50% below the "true" value, since the A.G.R.G. lead spectrographic results compare closely with accepted G_1, W_1 values; (h) titanium values obtained from the C.E. spectrograph tend to be very high, ranging from 9 to 10 times the A.G.R.G. spectrographic values in the 100 ppm range of the A.G.R.G. spectrographic results to 2 times in the 10,000 ppm range. Clearly the C.E. spectrographic titanium results are very much higher than true value since the A.G.R.G. titanium spectrographic results are relatively close to the accepted G_1, W_1 values; (i) vanadium values obtained from the C.E. spectrograph are close to A.G.R.G. spectrographic results, but do tend to be a bit lower in the 10 ppm range. This suggests that the C.E. results are to some extent closer to "true" value than the A.G.R.G. spectrographic results, since G_1, W_1 values from the A.G.R.G. spectrograph tend to be higher than the accepted values; (j) zinc values obtained from the C.E. atomic absorption tend to be about 50% lower than the A.G.R.G. spectrographic results. Since the A.G.R.G. G_1, W_1 values are close to accepted values, it would seem that the C.E. atomic absorption values are about 50% below true value.

These variations from "true" value and different levels of minor element content obtained by the various analytical techniques show how important it is not to compare directly results from the different rapid analytical methods. A simple correction could presumably be made if the difference in levels were known and a cross comparison required. In this study, however, no conclusions are based on the level of element values as indicated by the different analyses. Minor-element values of samples which had to be compared were always analysed by the same analytical method and as far as possible at the same time so that variations in minor-element level due purely to different analytical methods used or drift in value in the same method with time were not introduced.

4.4.6 Analytical Precision

Analytical precision is a more important measure of the analytical results than accuracy, since comparisons of minor-element contents were only made when the analyses were carried out by the same method.

The analytical precision has been calculated mainly by using duplicate analyses of a random selection of samples, usually about 1 sample every 5, 10 or 20 samples. The A.G.R.G. laboratory statistical series of 12 control samples for copper and nickel was used to calculate the precision of the initial drainage samples from Kadola and Provincial areas. A comparison of the values of the two measurements of precision are shown in table 6. Duplicate analyses of the initial drainage samples were made by taking every 20th sample and re-analysing it. The second analysis was carried out on a different plate from the first sample in order to check variations between plates. Samples taken during the second field season were split at the sample preparation stage after crushing and before sieving for the drainage sediments and soil samples, and after crushing and before pulverising the rock samples. In this way, errors due to sample preparation are included in the measurement of precision.

There are a number of advantages in the use of duplicate analyses for measuring the precision of multi-element analyses of a large number of samples of perhaps differing matrices:

(a) the precision measurement is carried out on the actual samples being analysed and not on a sample which might not have the same matrix,

Method of precision measurement	Elements	Initial drainage sediment sample data (AGRG Spectrograph)													No. of samples
		Co	Cr	Cu	Fe_2O_3	Ga	Mn	Ni	Pb	Sn	Sr	Ti	V	Zn	
Statistical	Precision*			40				31							average of 5 sets of 12 stat. series samples
Series	Range**			10-1000				10-1500							
Duplicates	Precision	39	39	61	70	68	58	41	87	51	20	60	49	50	38
	Range	8-230	13-850	3-500	0.01-23.2	1-60	5-3000	10-300	2-85	4-30	100-3000	300-11000	30-400	40-400	duplicates
Duplicate drainage sediment sample data analysed on C.E. Spectrograph and Co, Cu, Ni, Zn on C.E. At. Abs.															
Duplicates	Precision	43	61	70		68	59	54	41			34	50	49	30
	Range	10-325	40-300	10-3700		8-100	20-1500	10-120	4-400			6000-22000	40-400	10-2800	duplicates
Soil samples analysed on C.E. Spectrograph and Co, Cu, Ni, Zn on C.E. At. Abs.															
Duplicates	Precision	32	37	41		44	41	45	49			25	38	22	67
	Range	10-100	10-400	5-150		1-100	50-1000	5-460	4-70			3000-22000	10-500	7-135	duplicates
Rock samples analysed on C.E. Spectrograph and Co, Cu, Ni, Zn on C.E. At. Abs.															
Duplicates	Precision	37	40	50		67	66	57	53			68	66	37	53
	Range	10-80	40-250	5-1100		4-150	2-1500	10-170	2-500			500-24000	2-500	10-6000	duplicates

*Precisions are all at 95% confidence

**Range of analytical values in ppm except Fe_2O_3 which is in %

Table 6: Analytical precision of minor element analyses of drainage sediment, soil and rock samples from the provincial survey over Central Zambia

(b) a random selection of samples should give a fair range of the actual values encountered, and does not require any pre-knowledge of the distribution of the values. Thus it tends to be a truer measure of precision over the actual range of values encountered,

(c) a precision measurement for all the analysed elements can be calculated. It is difficult to make up a statistical series of control samples for more than 1 or 2 elements,

(d) very little extra sample preparation is necessary,

(e) greater ease and speed of calculation.

The main advantage and essential role of the statistical control samples is that the level of analytical value can be monitored between batches of analyses. This role can perhaps be fulfilled just as easily by the use of replicate analyses of certain samples which have a range of expected minor element variations of the samples.

The precision from the statistical series samples was calculated using Stern's (1959) method. The results quoted in table 6 for copper and nickel are the average of 5 sets of 12 statistical series samples.

The calculation of precision from duplicate analyses has been described by Khaleelee (1969). The actual precision measurement is equal to the percentage mean plus twice the standard deviation of the percentage differences between the pairs of duplicate analyses and is calculated as follows:

$$\text{If } PD_1 = \left(\frac{X_1 - X_2}{2}\right) \Big/ \left(\frac{X_1 + X_2}{2}\right) \times 100 \quad \%$$

Where PD_1 = percentage difference between each pair of analyses and

X_1, X_2 = values for each pair of analyses.

And $$\sigma_{PD} = \sum_{i=1}^{N} \frac{(\overline{PD} - PD_i)^2}{N-1}$$

Where σ_{PD} = Standard deviation of the percentage differences between each pair of analysis

$\overline{PD}$ = mean percentage differences between the pairs of analysis, and

N = number of pairs of analyses

Then $$\text{Prec} = 2\ \sigma_{PD} + \overline{PD}$$

Where Prec = Precision at the 95% confidence level.

This means that there is a 95% probability of obtaining a second value within the percentage measurement of the precision of the first value, assuming (a) a normal distribution to the differences between the values, and (b) a constant precision over the range of values encountered.

A computer programme in Fortran IV for the IBM 7094 has been written by the writer to carry out this calculation and is listed in the Appendix(1)The programme can calculate the precision for up to 13 elements at one pass. The output lists the precision of each element and the range of values over which the precision was measured.

The values for the precision for copper and nickel calculated by the statistical series control samples and the duplicate method are of comparable value (table 6). Therefore, the duplicate method was used thereafter as a measure of precision. The precisions for each element in the different groups of data are listed in tables 6 and 7. These precision values average about ± 48% at the 95% confidence level. This is within the generally quoted level of ± 50% for the spectrographic analytical method. However,the measurements range mostly between ±33 to ±68% within a total range from ±20 to ±87%.

Precision of analyses of Lusaka East samples

	Elements	Co	Cr	Cu	Fe_2O_3	Ga	Mn	Ni	Pb	Ti	V	Zn	Number of duplicates
Initial drainage sediment data from AGRG Spec.	Precision[1] Range[2]	35 4-60	36 20-300	60 1-85	26 1.2-20.0	44 3-40	36 40-1600	44 4-85	49 6-40	28 2000-11000	38 20-400	37 40-500	40
Duplicate & additional drainage sediment data from C.E. At.Abs. & Spec.	Precision Range	41* 10-70	45 40-250	38* 10-350		68 10-150	45 80-1500	24* 15-140	38 4-15	38 6000-22000	49 20-500	24* 20-250	25
Soil data from C.E. At. Abs. & Spec.	Precision Range	53* 10-200	43 40-600	47* 5-130*		66 8-100	60 50-1000	61* 2-500	58 4-100	47 2000-22000	69 10-1000	38* 10-301	40
Rock data from C.E. At. Abs. & Spec.	Precision Range	46* 10-80	48 40-200	68 5-170		52 2-200	79 4-2000	69* 1-200	55 1-50	42 3000-24000	75 1-400	59* 10-190	35

Precision of analyses of Kadola samples

Initial drainage sediment data from AGRG Spec.	Precision Range			40 5-500				27 30-1000					Average of 2 sets of 12 Stat. Series samples
Duplicate & additional drainage sediment data from C.E. At. Abs. & Spec.	Precision Range	34* 10-260	34 40-300	31* 5-600		37 8-70	59 4-2000	43* 10-360	42 1-20	22 4000-22000	49 5-800	32* 10-80	40
Soil data from C.E. At. Abs. & Spec.	Precision Range	36* 10-100	41 40-1000	41* 10-290		58 8-80	68 4-900	40* 10-290	24 4-60	30 3000-22000	49 5-800	25* 10-80	79
Rock data from C.E. At. Abs. & Spec.	Precision Range	32* 10-790	40 40-300	33* 5-2600		46 8-100	72 4-4000	55* 10-1000	41 1-5	44 1000-25000	52 4-500	29* 10-150	22

[1] Precision is at 95% confidence level

[2] Range is ppm except Fe_2O_3 which is in %

[3] Precision is of Cu and Ni only as measured from a Statistical Series of test samples

*Co, Cu, Ni, Zn were analysed by atomic absorption whilst the remainder were analysed spectrographically by Chartered Exploration

Table 7: Analytical precisions of minor-element data of drainage sediment, soil and rock samples collected in Lusaka East and Kadola areas.

4.4.7 Drainage Sampling Precision

During the second field season drainage samples were retaken from 84 of the locations sampled during the first field season. These samples were analysed for 10 elements at Chartered Exploration laboratories. The initial samples taken during the first field season had been analysed on the A.G.R.G. spectrograph. In order to make the two sets of analyses comparable, the values were standardised in terms of the means and variances of their distributions. These were calculated using Garrett's (1967) histogram programme described in section 4.5.2 which has an option for calculating standardised values. The duplicate precision programme was then used in order to calculate an overall sampling and analytical precision from the standardised values of the analyses of the duplicate samples.

The sampling and analytical error is usually just under twice the analytical error (table 8) with an average of 79% for all the elements.

4.5 DATA HANDLING METHODS

4.5.1 Introduction

During the first phase of this work the results of 13 elements from over 3000 samples from the provincial and regional surveys were plotted and evaluated. Subsequently, a further 2200 samples were taken and analysed for 10 elements. A total of some 61,000 items of numerical data had to be processed. This could only be done in a consistent thorough method, making use of all the data, by computerised and statistical techniques.

For this purpose all the data was punched on to computer cards with sample number and easting and northing coordinates. The

	Total precision. Analytical + sampling precision	average analytical precision
Co	100	41
Cu	72	66
Cr	90	50
Ga	68	68
Mn	78	58
Ni	86	50
Pb	65	64
Ti	85	47
V	82	50
Zn	68	49
79% Average total precision		

Table 8 Sampling precision of drainage sediment samples.

data could than be plotted automatically, frequency distributions and histograms could be drawn, and basic parameters, such as mean values and standard deviations, could be calculated for the different elements for different types of samples. Statistical and mathematical techniques, such as moving average and factor analysis programmes, could also be applied to the data.

4.5.2 Histogram plotting and calculations of basic statistical parameters

All frequency distributions, means and standard deviation measurements have been plotted and calculated using a computer programme compiled by Garrett (1967) and adapted for use on the IBM 7094 at Imperial College by Khaleelee (1969). This programme also has a number of options, including logarithmic transformation of the data, a Chi-Square test for normality on the plotted histograms, a computation of a product-moment correlation coefficient matrix, from which eigen-values are extracted, and a matrix of Student's t values to test the significance of the correlation coefficients, calculation, listing and/or punching out of the standard normal deviates, and the plotting of scattergrams of all pairs of variables. The skew and kurtosis of each histogram are always calculated to indicate the divergence of the distributions from normality and their peakedness, respectively. Anomalous samples with values greater than two standard deviations can also be extracted from the data and listed.

4.5.3 Automatic CALCOMP Plotter

Minor element values, factor scores and moving average values were all plotted using the CALCOMP (Californian Computer Products Ltd.) X, Y digital incremental plotter. This automatic plotter utilises the movement of a drum, over which paper is threaded, for plotting along one axis and movements of the pen, in a direction parallel to the axis of the drum, for plotting along the axis at right angles. The maximum size of a map is determined by the width of the drum (29 ins) and the maximum length of the roll of paper (120 ft). The plotting is done relative to a scale, and coordinate origin established by the user. The element values are then plotted relative to these defined grid coordinates. The manufacturers claim a plotting precision to within 0.01 inch. The size of the printed title and metal values can be chosen by the user down to a minimum size of 0.05 inch, but 0.07 inch was found to be a minimum legible size.

The CALCOMP plotter is activated by a magnetic tape generated from a computer programme and the data. The computer programme was written by Khaleelee (1969) with minor adaptions by the writer using the various plotting subroutines available from the manufacturers.

The main advantages of this method of plotting data are the saving of man hours, the accuracy of plotting, and the elimination of operator error. The cost, however, might be prohibitive both in computer and CALCOMP time if this equipment were not already freely available in such a place as a university. Overheads on manual plotting, however, are also high.

The CALCOMP plotter is really designed for drawing graphs and is not at its most efficient when plotting individual points. It takes about ½ an hour to plot 1286 data points on a (27"x25") map using 0.07 inch characters for the sample values when the data is reasonably well sorted. If the data is not sorted the plotting time can be considerably longer since the plotting time is directly proportional to the distance the pen has to travel. In addition all the data on a second tape are not always plotted with reference to the original defined axes.

4.5.4 Moving average analysis

The contouring of untreated geochemical reconnaissance data is usually difficult due to noise created by the combined sampling and analytical errors. Of the two methods known for smoothing data, the moving-average analysis appeared to be the most appropriate for elucidating background variations of the minor elements. Trend surface analysis was considered but eliminated because the data did not fulfill the assumptions necessary for the correct application of a trend surface model, namely: (a) there are over 1000 sample values to be processed. This is considerably more than the optimum number of 300 suggested to give a meaningful trend surface interpretation (Agterberg, 1964), (b) the samples are not on a regular grid, which according to Nordeng (1965), might give rise to surfaces bearing little relation to geological trends, (c) the trend surface model is most applicable to data levels which change in some continuous manner such as grain size or density of sediment particles controlled by some natural force such as a river current or slope. Regional minor element values, on the other hand, are more likely to change sharply in level due to different lithologies and other factors controlling regional minor element content.

The other points which suggested that moving average analysis would be the more appropriate method were: (a) the moving average results from Sierra Leone which gave a closer correspondence to the geology than polynomial trend surface analysis (Garrett, 1966), and (b) the similarity of the calculation of moving averages to the calculation of background values. In normal geochemical reconnaissance geochemical background is defined as the mean of minor element values within the sampled area. The moving averages are simply the means of the values of samples within adjoining or overlapping areas.

The moving average analysis used may be regarded as a two dimensional extension of the one dimensional method of moving averages. The technique averages values within defined search areas, thus smoothing the noise from individual samples. The size, shape and degree of overlap of the search areas can be chosen by the user.

Khaleelee (1969) has combined the moving average programme with CALCOMP plotting routine so that the moving averages within each search area are plotted automatically. The moving averages are plotted at the centroid of the sample points within the search area to avoid bias due to irregularly spaced data. The original moving-average programme was written by Dixon and Khaleelee (Khaleelee, 1966).

In this study a square search area of 30 x 30 miles with an overlap of 50% has been used. The 900 square mile search area was used because it is approximately the size of areas over which background values might be assessed during the course of regional geochemical reconnaissance and mineral exploration in Zambia. An overlap of 50% was used as a reasonable optimum size because: (a) increasing the overlap to 75% created more moving average points than original samples, which would have been of doubtful statistical or geological value, and (b) for the practical reason that more moving average points would be generated than could be included on one Calcomp magnetic tape if a much greater overlap than 50% were used. The 900 square mile search area has resulted in there being an arithmetic average of 16 samples per search area. There are a total 280 search areas, of which 46 or

16% have below 5 samples and the rest have mostly from 5 to 28 samples inclusive, with a mode of 107 search areas or 38% having between 17 and 24 samples inclusive (fig. 11). The number of search areas with below 5 samples in them are the result of search areas along the edge of the sampled area. Comparatively little reliance can be placed on these values, and, therefore, the contours near the edge of the sampled area. The frequency distribution of the number of samples per search area (fig. 11) also gives some indication of the variation of sample density. There is modal sample density of about 1 sample every 50 square miles with a maximum of 1 sample every 16 square miles and a minimum of 1 sample in 180 square miles, excluding those search areas with below 5 samples.

4.5.5 R-mode factor analysis

It is difficult, if not impossible, to interpret controlling features from the variations of a single element over an area. Interpreting controlling features would be easier from associations of strongly correlated variables from multi-element data. Strongly correlated elements can be simply evaluated from the correlation matrix, but it is not possible to then show the regional distribution of the controlling features. R-mode factor analysis and the calculation of R-scores was used in this project, firstly in an attempt to overcome this interpretational problem, and secondly to show that multi-element geochemical data collected for mineral exploration, and used up till now only for the detection of anomalous samples, can be more rigorously evaluated so as to give useful information on the features and their geographical distribution controlling the minor element content in geochemical samples. Q-mode factor analysis has been used with some success in

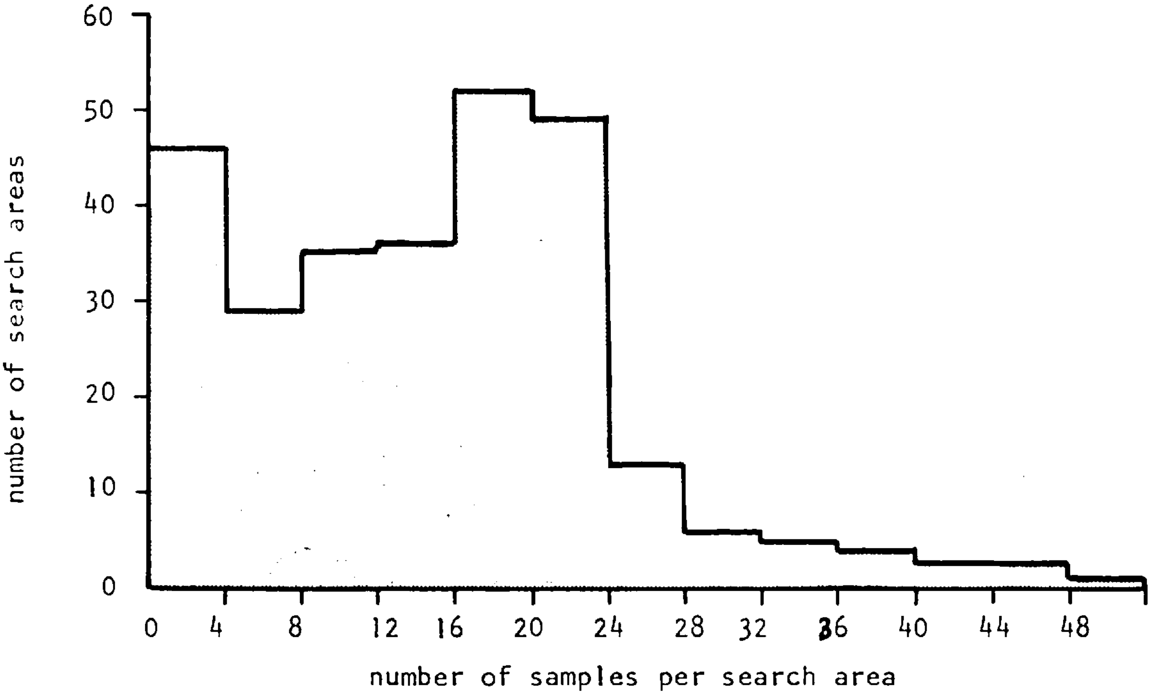

Fig: 11 Frequency distribution of number of samples per search area of moving average analysis.

Sierra Leone (Garrett, 1966) and concurrent with this research, R-mode factor analysis, with factor scores for giving a measure of the dominant factor controlling the minor-element values in a sample, was being evaluated on drainage samples from U.K. (Khaleelee, 1969).

Detailed descriptions and background of the use of factor analysis in geology (Garrett, 1966; Khaleelee, 1969) and the theoretical background (Harman, 1967), have been given elsewhere (Garrett, 1969; Saagar and Esselaar, 1969). A brief outline of the method and some of its limitations will be given here.

Factor analysis is a mathematical procedure which sets out to recognise the underlying features contributing to the variations of a set of complex numerical data. Or more exactly it defines associations of highly correlated variables (R-mode) or samples (Q-mode) in a hierarchic order from which the actual factors controlling the variation of the data might be interpreted. A geochemical example would be the factor analysis of a number of element values of feldspars of differing composition, which should show that their variations in composition could be expressed in terms of three end members (Q-mode) or element associations (R-mode) corresponding to Na, K and Ca feldspars.

The starting point of any factor analysis is the correlation matrix. There are two basic correlation matrices possible from a set of data from which the two modes of factor solution are derived. The Q-mode method utilises the correlations between the variables whilst the R-mode method utilises the correlations between the variables. The Q-mode was eliminated as a practical method for this study for much the same reasons as Khaleelee (1969) rejected it in favour of R-mode for the evaluation of the U.K. regional data (section 2.2.3) namely: (a) the limitation of the number of samples to 100, and

(b) the difficulty interpreting the Q-mode solution in terms of end member samples of extreme composition.

The following description of factor analysis will be entirely in terms of R-mode, although the principles of the two methods are similar once the relevant correlation matrix has been evaluated.

The R-mode analysis programme used in this study was compiled by Garrett (1967). It proceeds from an analysis of the correlation coefficient matrix, where the product moment correlation coefficient (r_{jk}) between two variables (x_j, x_k) with means of $\overline{x_j}$, and $\overline{x_k}$ is given by:

$$r_{jk} = \frac{\sum_{n}^{i=1}(x_{ji} - \overline{x_j})\ (x_{ki} - \overline{x_k})}{\sqrt{\sum_{n}^{i=1}(x_{ji} - \overline{x_j})^2 \quad \Sigma(x_{ki} - \overline{x_k})^2}}$$

where n = to the number of samples.

This correlation coefficient is a measure of the linear relationship between two variables and its value lies between +1 and -1 depending on whether the variables are related sympathetically or antipathetically, respectively. A zero correlation coefficient would signify no correlation at all between the two variables.

To proceed to a factor solution two assumptions have to be made: (a) that each variable (x_i) can be expressed in the form

$$x_i = a_{i1}f_1 + a_{i2}f_2 + \ldots + a_{im}f_m + a_{iu}u_i$$

where a_{im} = the relative importance of the common factor f_m and is called a 'factor loading' of the factor f_m. It can be thought of as a measure of the correlation of the variable with a factor and varies between +1 and -1 with the same meaning as a correlation coefficient, and u_i = the factor unique to the particular variable in question, and (b) that there are fewer factors than variables.

For a true factor analytical solution the unique factor must be found. It is only possible to find this unique factor if the values for the principle diagonal in the correlation matrix, that is the correlations of each variable with itself, are known and inserted. It is generally agreed that the ideal value to be inserted should be the communality, where the communality is the sum of the squared factor loadings for each variable and is a measure of the degree to which the factors account for the variance of each variable. The communality can vary between 0.0 and 1.0. The latter value implies that all the correlations of a variable have been accounted for by the factors, the former value implies the opposite. The communality, however, is not known until after factor analysis and there is still considerable controversy about possible alternative values to the communality which can be placed in the principal diagonal in order to find a true factor solution.

Most geological workers up till the present have simply considered the common factors, neglected the unique factor and placed 1.0 in the principal diagonal. This results in what strictly should be called a 'principal components' solution (Harman, 1967). Since unity is placed in the principal diagonal of the correlation matrices which have been factored in this project, the 'factors' referred to in this thesis, and by other geologists using this technique, should be termed 'principal components' (Cameron, 1967). The former nomenclature, however, is already well established in the geological literature and will be adhered to in this thesis to avoid confusion.

The dimensional reduction from the variables to fewer factors is carried out by choosing the first and each succeeding factor so that a maximum amount of variance is accounted for. Visualised geometrically these factors (principal components) might be thought of as axes around which variable vectors are clustered. The extent to which each variable (x_i) contributes to each factor is termed the 'factor loading' (a_{in}), which is equivalent to the correlation of the variable with the factor and varies between +1.0 to -1.0 in the same way as a correlation coefficient. Visualised geometrically, the factor loading would be equal to the projection of the variable vector on the principal factor axes. These principal factor axes can then be rotated so that they correspond more closely to the variable vector clusters. These axes are still orthogonally related in multi-variant space; that is to say uncorrelated. In the geochemical environment it is likely, however, that factors are correlated and not orthogonally related. An oblique solution is possible in which the restriction of orthogonal or uncorrelated factors is neglected. Under oblique conditions, therefore, the factors will be, to some extent, correlated.

The practical result of an R-mode factor analytical solution of a set of multi-element geochemical data is a matrix of element loadings on the number of factors extracted in a particular factor solution; or in other words, element associations defined by those elements which have high factor loadings in the same factor. The number of factors to be extracted from a set of data is largely a subjective choice, although criteria for choosing a 'correct' number of factors have been suggested (Harman, 1967). Ultimately, however, the choice still relies on the subjective interpretation of the researcher. In geochemical work this can only be based on the ability to explain the element associations, produced by a factor solution, in terms of the known or likely associations of the elements in the geological environment that has been sampled. The level at which a factor loading on an element in any particular factor is significant must also be established and there is still much controversy on the meaningful factor loadings. The method used in this project will be discussed later.

Having selected the appropriate number of factors it is necessary to interpret the associations. It has been shown in a recent study on simulated geochemical data that although R-mode factor analysis can choose the correct number of factors and the general groupings of the elements that the original structure is not necessarily extracted (Miesch, 1969). That is to say, the natural factor or controlling feature might not correspond to the axis at the centre of a cluster of measured variables. This implies that the elements with the highest loadings in an association extracted by factor analysis are not necessarily the most important variables in terms of measuring the natural controlling features. The factor associations must be interpreted with care, therefore, and the elements included and the likely geochemical groupings known from past experience taken into account.

One of the main problems with the R-mode factor solution in geochemical problems is that samples are not readily classified in terms of the extracted factors. In most geologic problems the areal distributions of factors or data in general are required. The Q-mode factor loadings on the samples can then be plotted directly on to a map and used to show the area of influence of each factor. The element associations derived from the R-mode solution, on the other hand, have to be related to the samples by a further calculation showing the extent to which each factor is represented in each sample. There have been a number of methods proposed for calculating such a factor value for each sample (Harman, 1967; Cameron, 1967). The method used in this study is that described by Harman (op. cit.) as the method of 'ideal variables' and gives an approximate factor measurement for each sample. These are termed factor R-scores by Garrett (1967) and will be referred to in this thesis as such. They are calculated as follows:

$$R_{ij} = \sum_{N}^{k=1} V_{kj} Z_{ki}$$

where R_{ij} = the factor score of sample i on factor j

V_{kj} = the factor loading on element k on factor j

Z_{ki} = the standardised concentration of element k on sample i

N = the number of elements used in the R-mode analysis

The limitations of R-mode factor analysis are set by the assumptions which have to be made to apply it: (a) factor analysis rests on the principle of parsimony, that is to say, the explanations for a set of data must be simpler than the data, in other words there must be fewer controlling features than variables measured. This will only be true if there are, not only more variables than features, but also that the features are measured in some degree by one or more of the variables. In a geochemical context it is possible to conceive of a problem in which there are more bedrock types and secondary environmental influences on the minor elements than minor elements that have been measured. However, it will be shown that using the minor elements that have been analysed the gross geological features are described by the factors. Presumably more geologic differentiation would be possible with a different selection of element analyses. (b) Other assumptions centre around the statistical significance of the initial correlation matrix on which the factor analysis is based. Firstly the variables must be linearly related and secondly they must be as near normal as possible. The linear relationships of some of the minor elements in this study have been checked on visual plots of one element against the other for the initial drainage data. In general, it appears to be a fair assumption for most of the elements, except for tin and strontium which have truncated distributions. The frequency distributions of most of the elements used are positively skewed. They have, therefore, all been log transformed to the base 10 in order to normalise them. However, the normality of these distributions could be improved if a separate transformation appropriate to each variable distribution could be carried out on each variable rather than the same transformation on all variables.

There are a variety of different methods for manipulating the correlation matrix between variables which come under the general heading of R-mode factor analysis and have been incorporated into computer programmes. The computer programme used in this study was compiled by Garrett (1967) and adapted for the IBM 7094 at Imperial College by Khaleelee (1969). This programme uses versions of the Manson and Imbrie (1964) fortran 11 factor analysis programme modified by Cameron (1967). The Varimax criteria for rotation (Kaiser, 1958) and the Promax method to obtain an oblique solution (Hendrickson and White, 1964) are used. Factor R-scores for the samples were calculated using Harman's (1967) method of ideal variables.

CHAPTER FIVE

RESULTS OF PROVINCIAL RECONNAISSANCE

5.1 MINOR ELEMENT PATTERNS FROM DRAINAGE SEDIMENT SAMPLES

5.1.0 Introduction

Visual inspection of the maps of the minor element data revealed some regional variations of background values. These data, however, are very noisy due to sampling and analytical errors, and due to real variations related to geology. This makes objective contouring and interpretation extremely difficult. For this reason, moving average analysis was used to smooth the data. The moving average values were contoured and the resulting distribution patterns for the elements are illustrated (Figs. 12-25). The moving average parameters, such as search area size and overlap are as described in section 4.5.4. The elements related to metallogenic provinces will be described first, followed by those that appear to be controlled mainly by lithological or stratigraphic, and secondary environmental features respectively, and lastly by those elements showing no apparent relation to known features.

The moving averages, since they are simply an average of values within an area, can be thought of as simply background values (see section 4.5.4) and will be referred to as such in the following descriptions.

5.1.1 Element distribution patterns shown by moving average analysis

The contoured moving-averages are illustrated in figures 12 to 25 and show the following features:

(a) Copper background variations show Copperbelt values to be twice those in the Broken Hill area to the south (Fig. 12). A belt of medium to high background runs through Lusaka with local highs to the east and west. There are also higher values along the northwest edge between Lukanga swamp and the Copperbelt and in the southwest corner around Livingstone. It was thought possible that some of the high background areas might be due simply to the inclusion of a few highly anomalous samples; therefore, samples with copper values greater than 96 ppm, which corresponded to a threshold level at two standard deviations above the overall mean, were ommitted from a second moving average computation. The resulting map (Fig. 13) shows essentially similar patterns to those in Fig. 12 although the levels are somewhat reduced in the higher background areas.

(b) Cobalt background variations (Fig. 14) show a similar distribution to copper. Areas in the Copperbelt are about 1.7 times greater than the lower values. East and west of Lusaka two areas are about 1.5 times greater than the low areas. High cobalt background also occurs in the Livingstone area.

(c) Tin background distribution (Fig. 15) shows a concentration of values greater than 8 ppm in the Choma tin belt. Mostly, the tin background is shown as below 6 ppm. Because tin has a detection limit of 5 ppm, only the obviously high tin areas show up and the true background distribution patterns cannot be evaluated.

(d) Strontium background concentrations (Fig. 16) are twice the detection limit of 100 ppm in the Feira carbonatite area, over three times in the Livingstone area, and over 1.5 times in the Kadola area south of Kitwe.

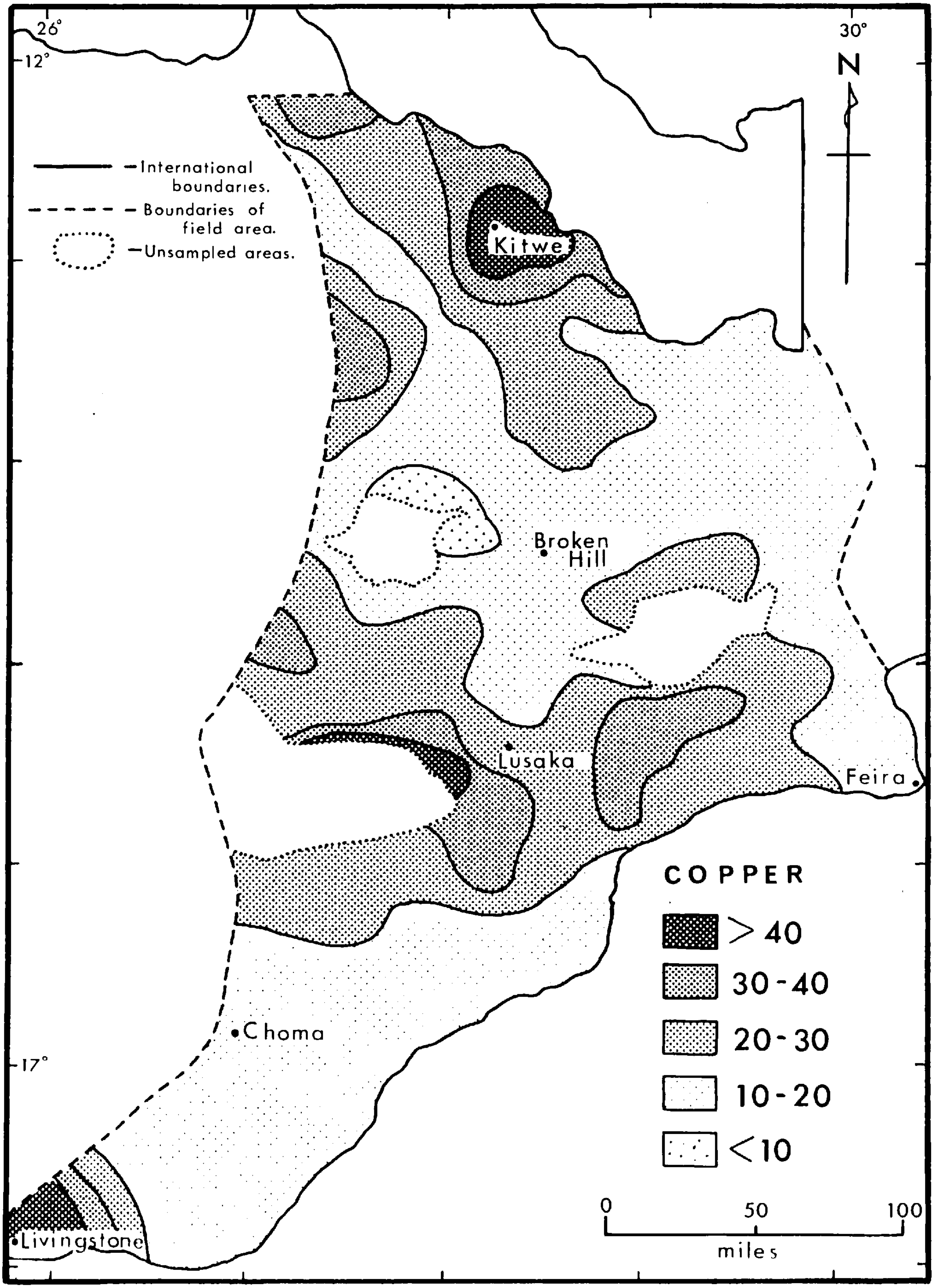

Fig: 12 Copper content of drainage sediment (including all samples).

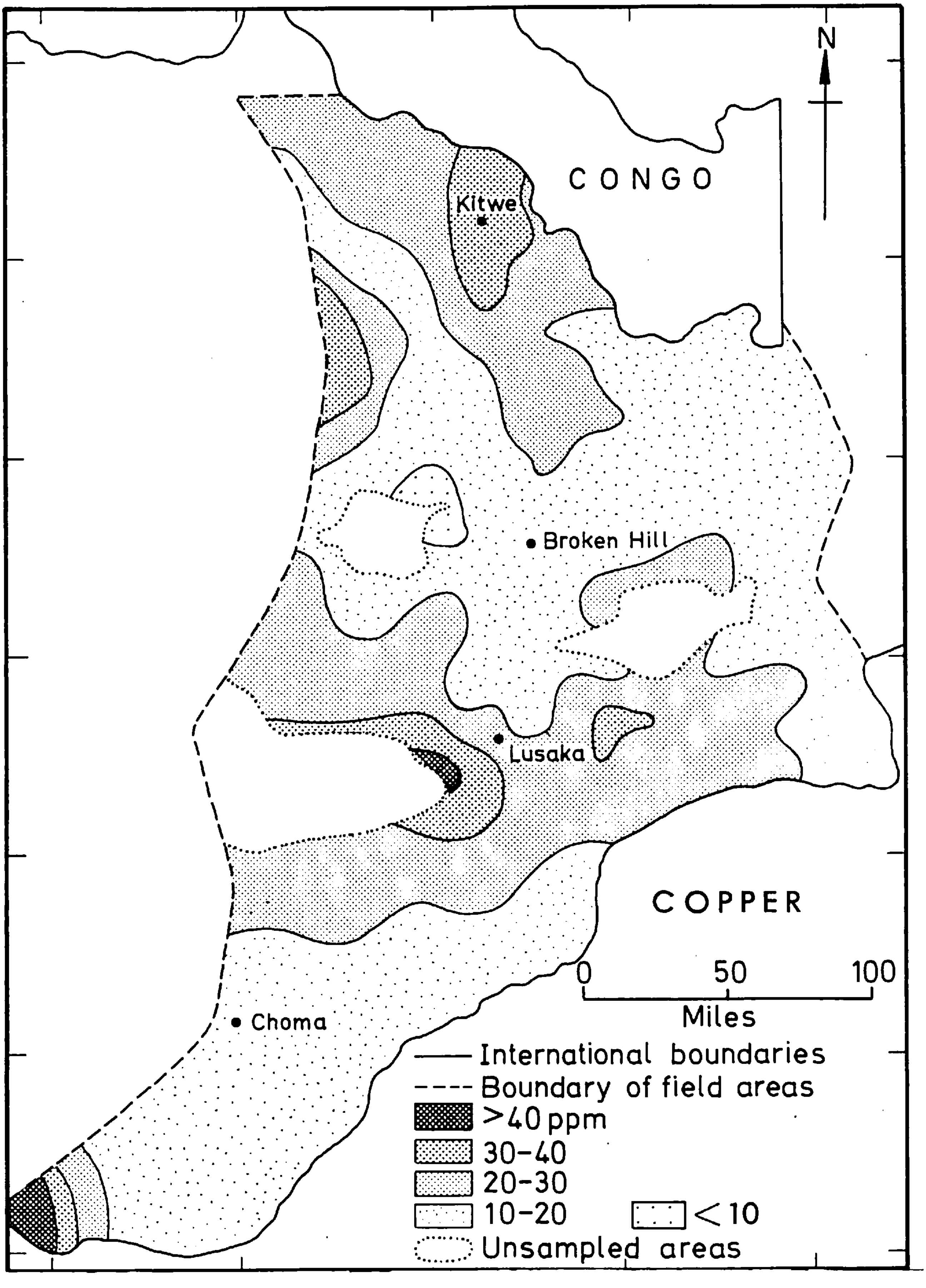

Fig: 13 Copper content of drainage sediment (omitting anomalous samples).

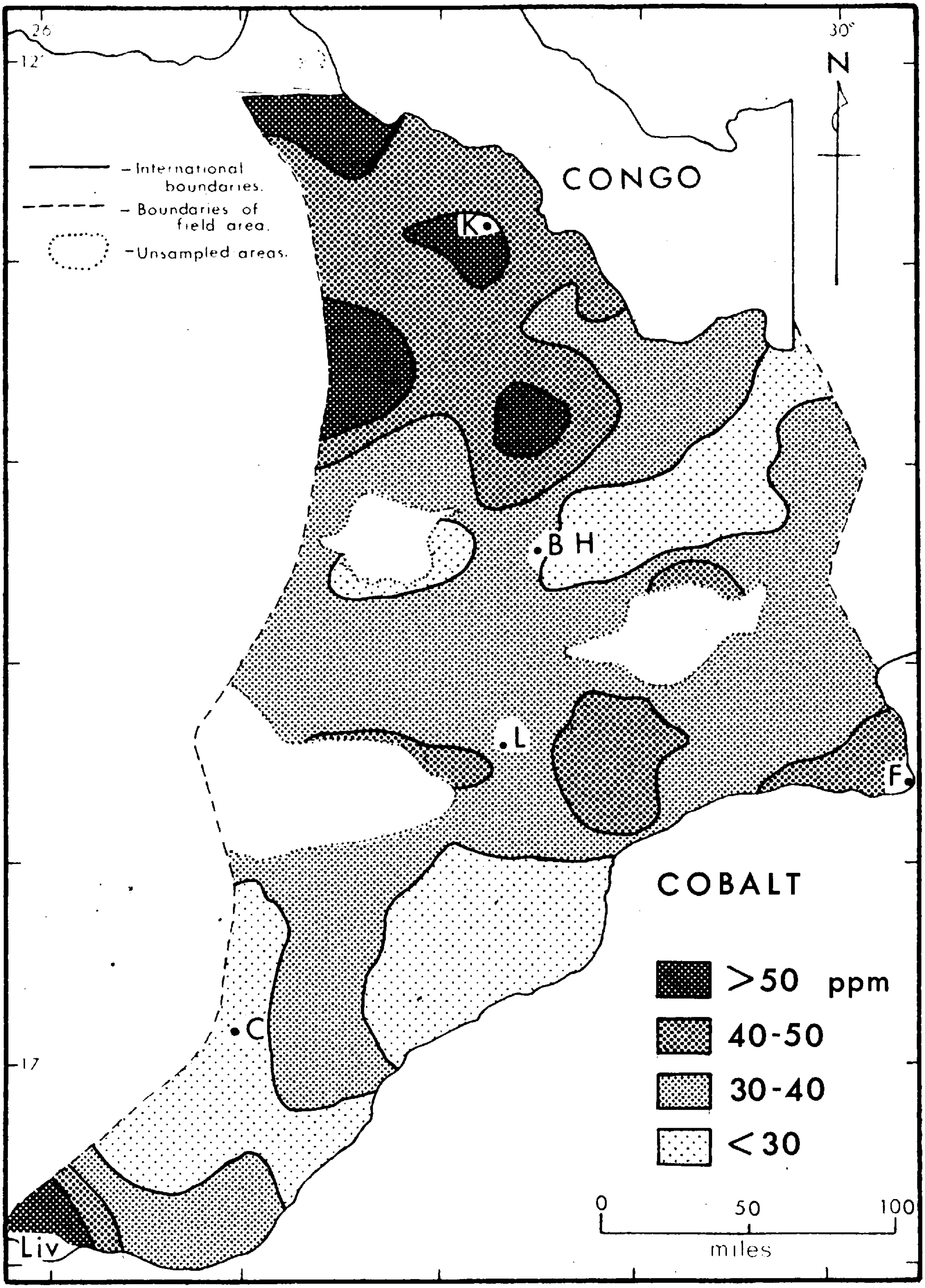

Fig: 14 Cobalt content of drainage sediment.

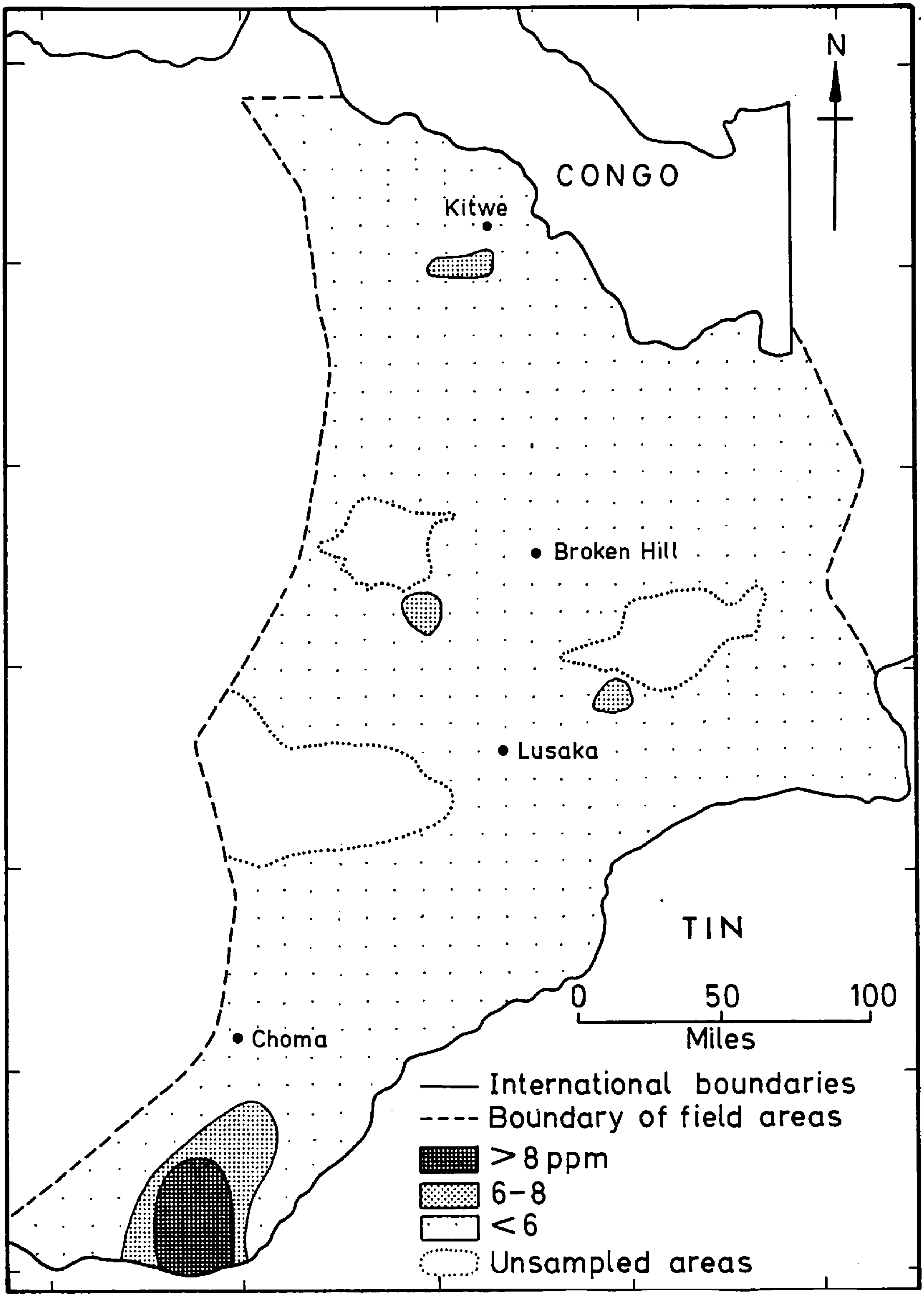

Fig: 15 Tin content of drainage sediment.

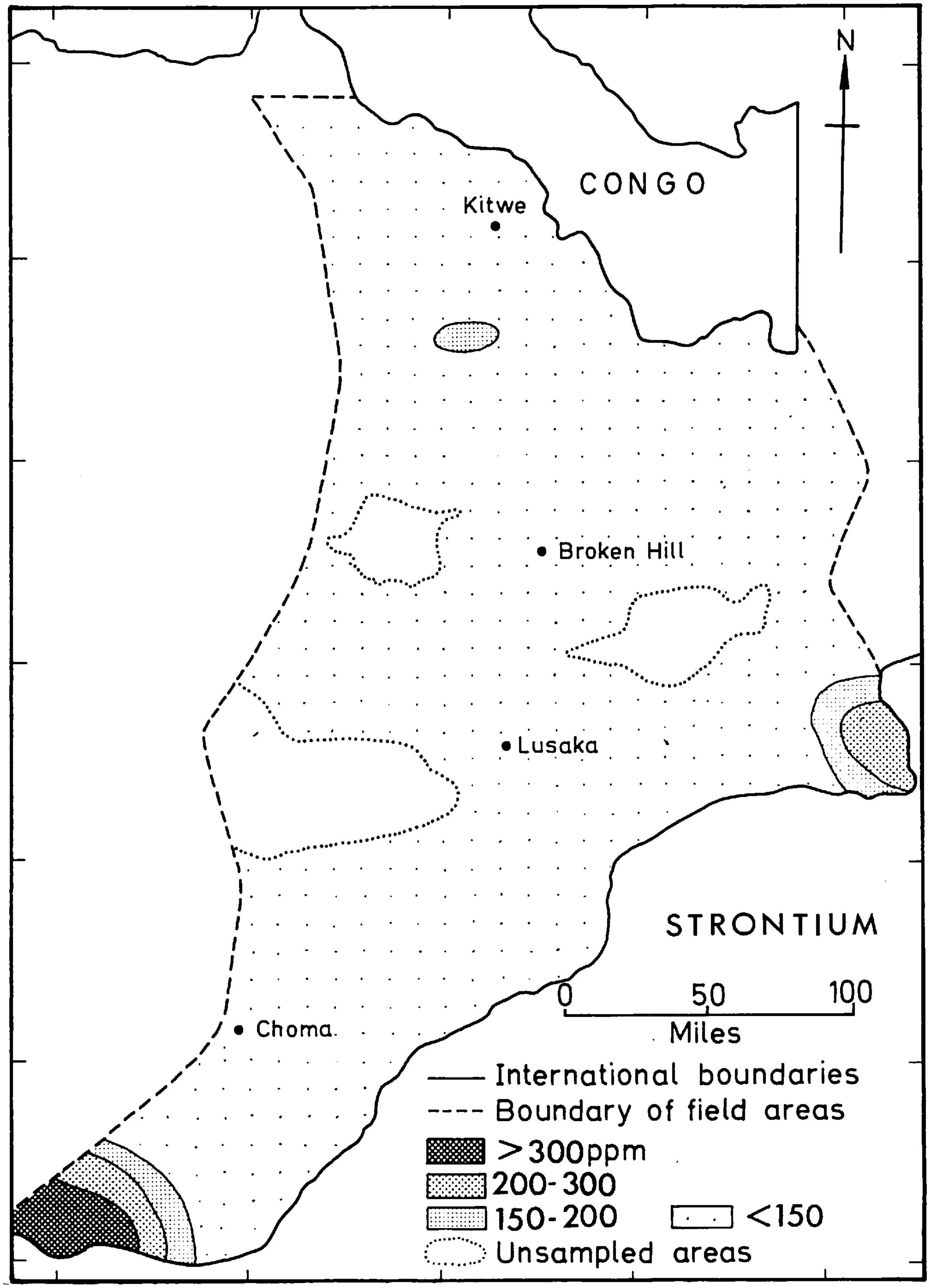

Fig: 16 Strontium content of drainage sediment

(e) The 30 ppm zinc contour divides the field area more or less in half (Fig. 17), with the east and south having a background greater than 30 ppm and reaching 50 to 70 ppm in places, and the north and west having a background of less than 30 ppm. Zinc background in the Livingstone area is greater than 70 ppm.

(f) Lead background (Fig. 18) is highest in the southwest, excluding the extreme southwest around Livingstone, and in parts of the eastern half of the field area. There is a limited area of high values just west of Lukanga swamp.

(g) Manganese background variations (Fig. 19) show a marked two-to-threefold enhancement of values in the south compared to the north of the field area. The highest background areas over 550 ppm occur in the escarpment areas in the southeast, west of Feira and in the southwest, east of Livingstone.

(h) Ferric iron background variations (Fig. 20) show a comparable distribution to manganese in so far as the background is mostly below 3% in the northern half of the field area and greater than 3% in the southern half. The highest background areas, over 7% are largely in the southeast and southwest around Livingstone.

(i) Vanadium background variations (Fig. 21) have similarities to the manganese and iron distributions with an area in the north having below 70 ppm and a general increase to the south. There is, however, a considerable area in the southwest with a background between 70-100 ppm and a small area around Choma of below 70 ppm. There is a belt of high background between 100 and 200 ppm running east-west between Feira and Lusaka to the western boundary of the field area. In the Livingstone area the background increases to greater than 200 ppm.

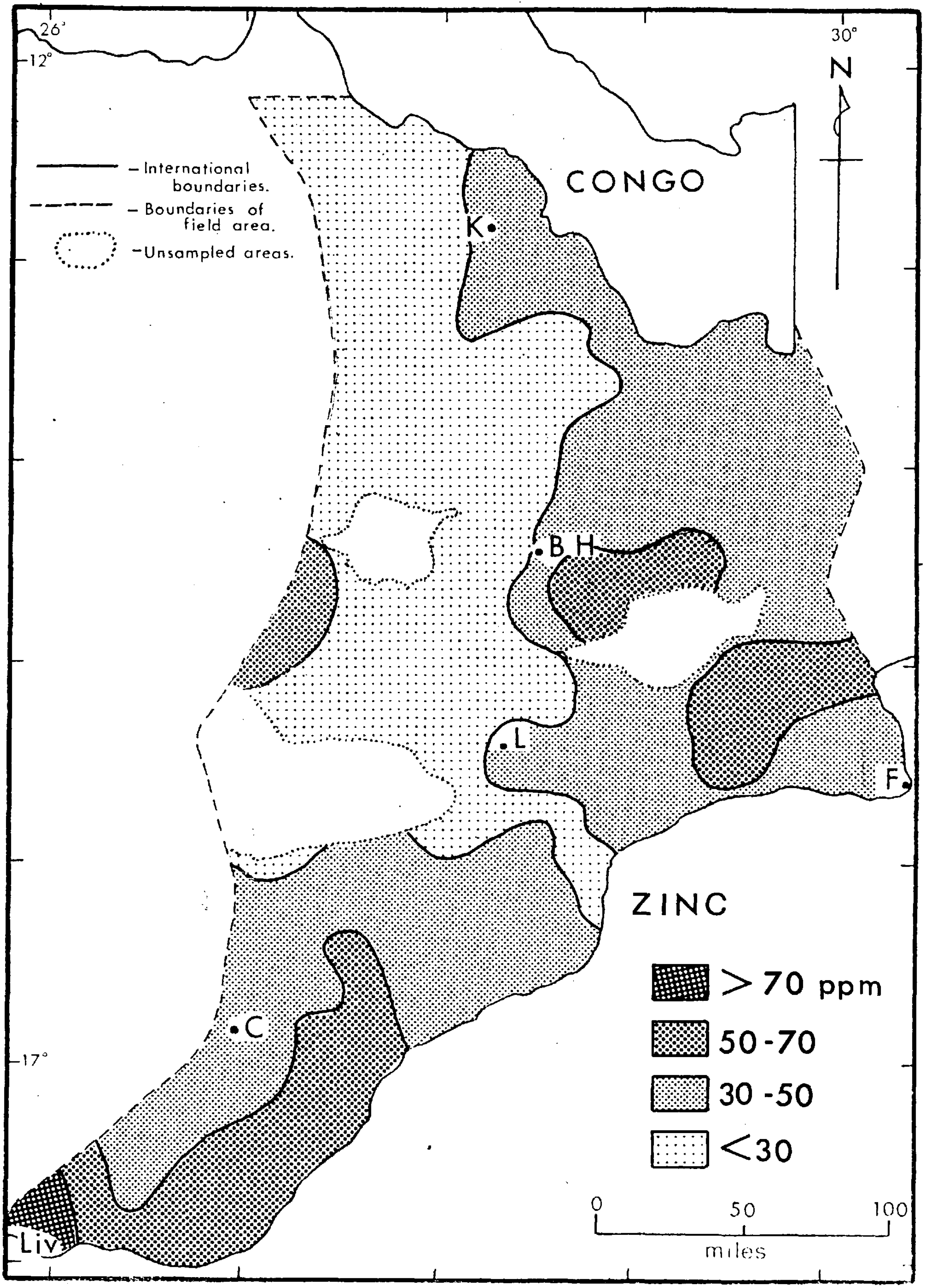

Fig: 17 Zinc content of drainage sediment.

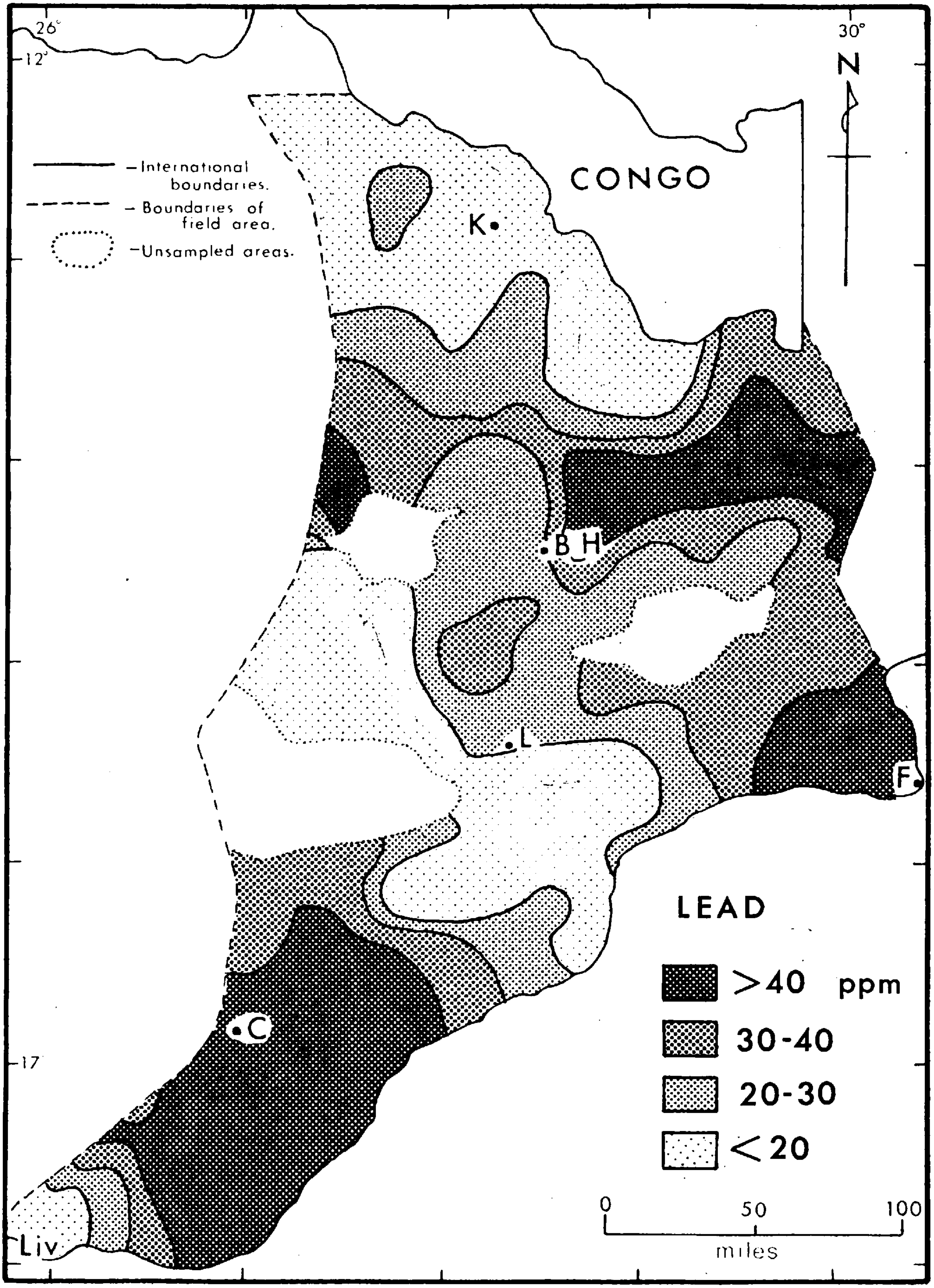

Fig: 18 Lead content of drainage sediment.

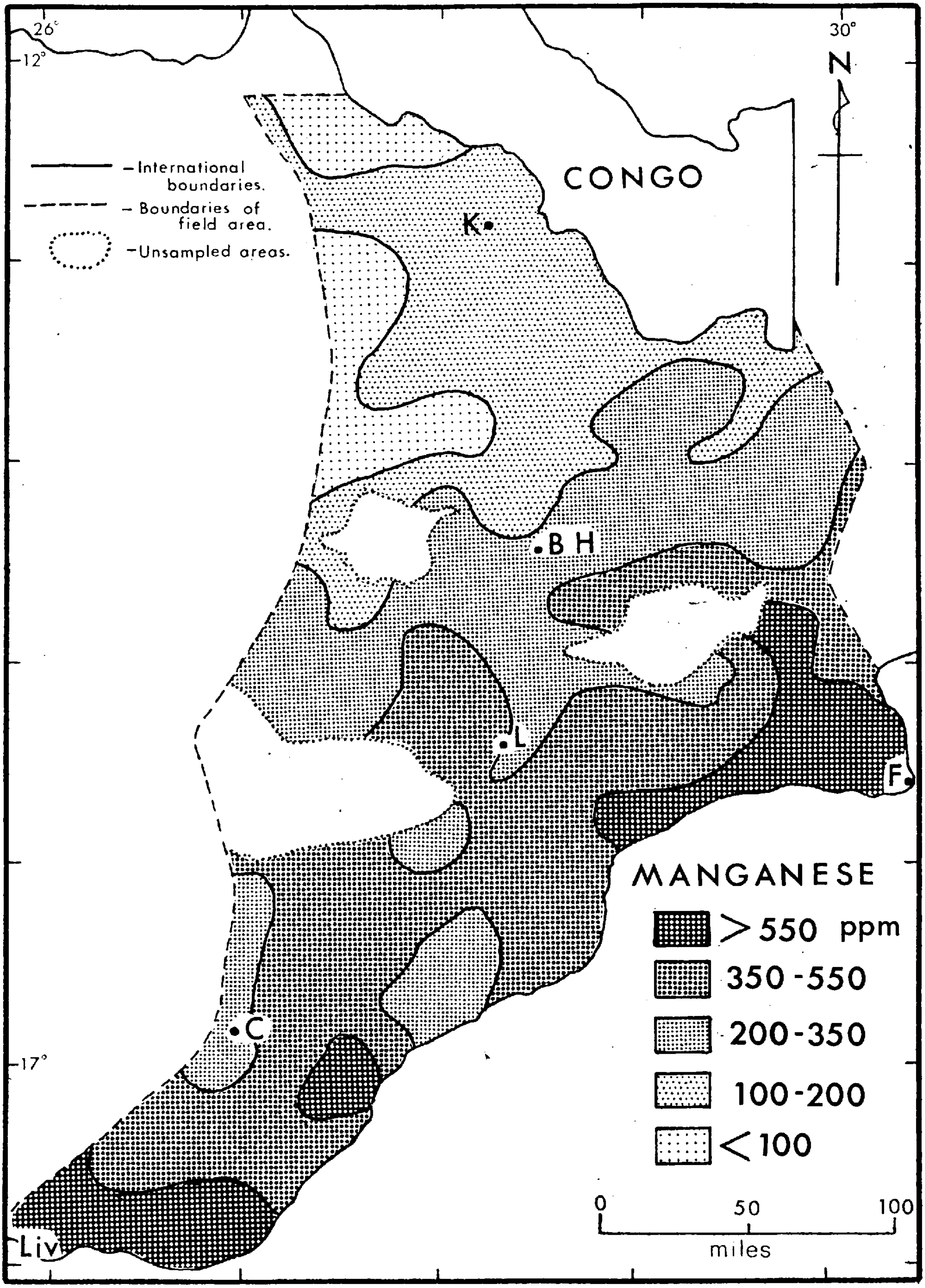

Fig: 19 Manganese content of drainage sediment.

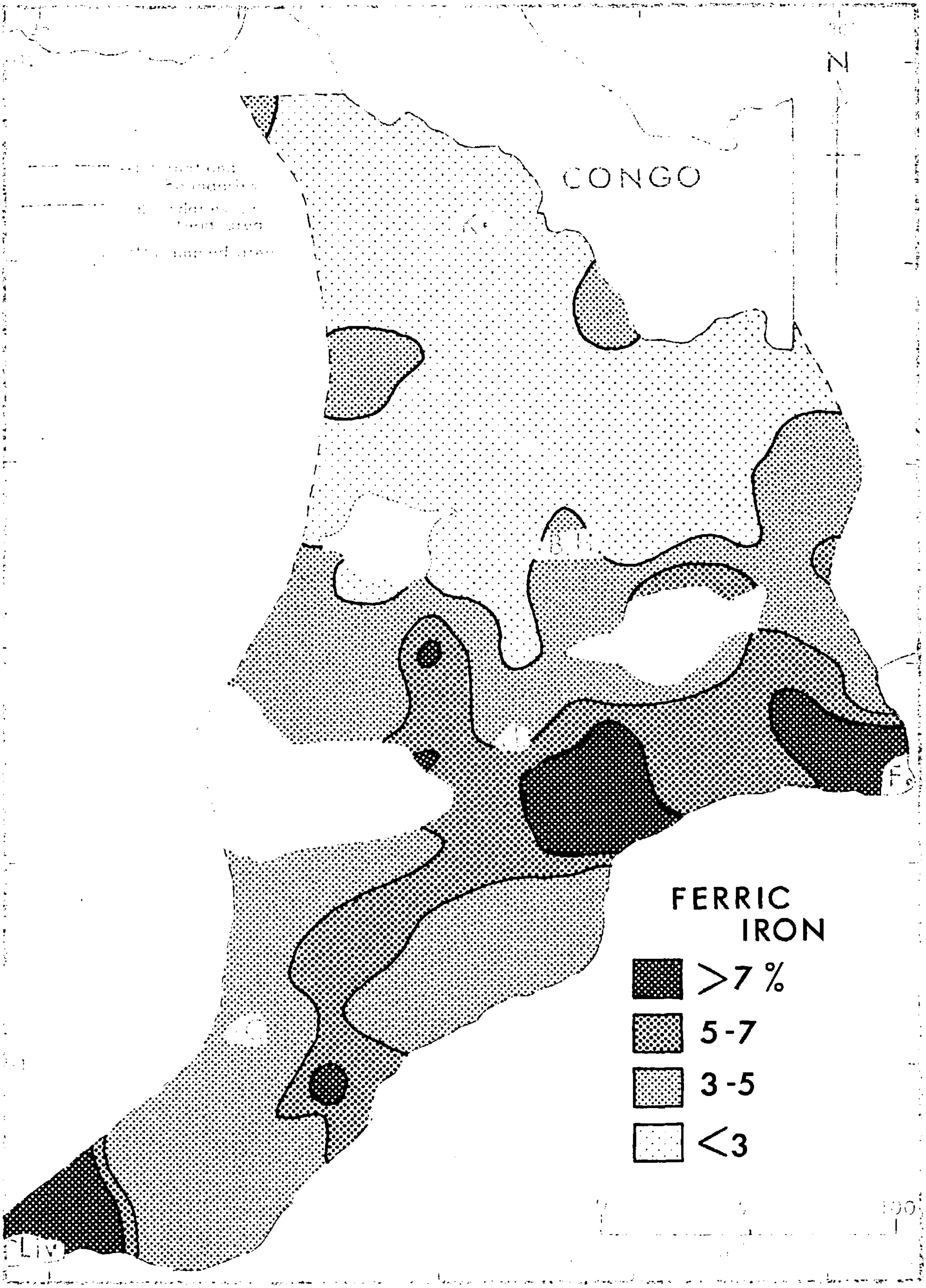

Fig: 20 Ferric Iron content of drainage sediment.

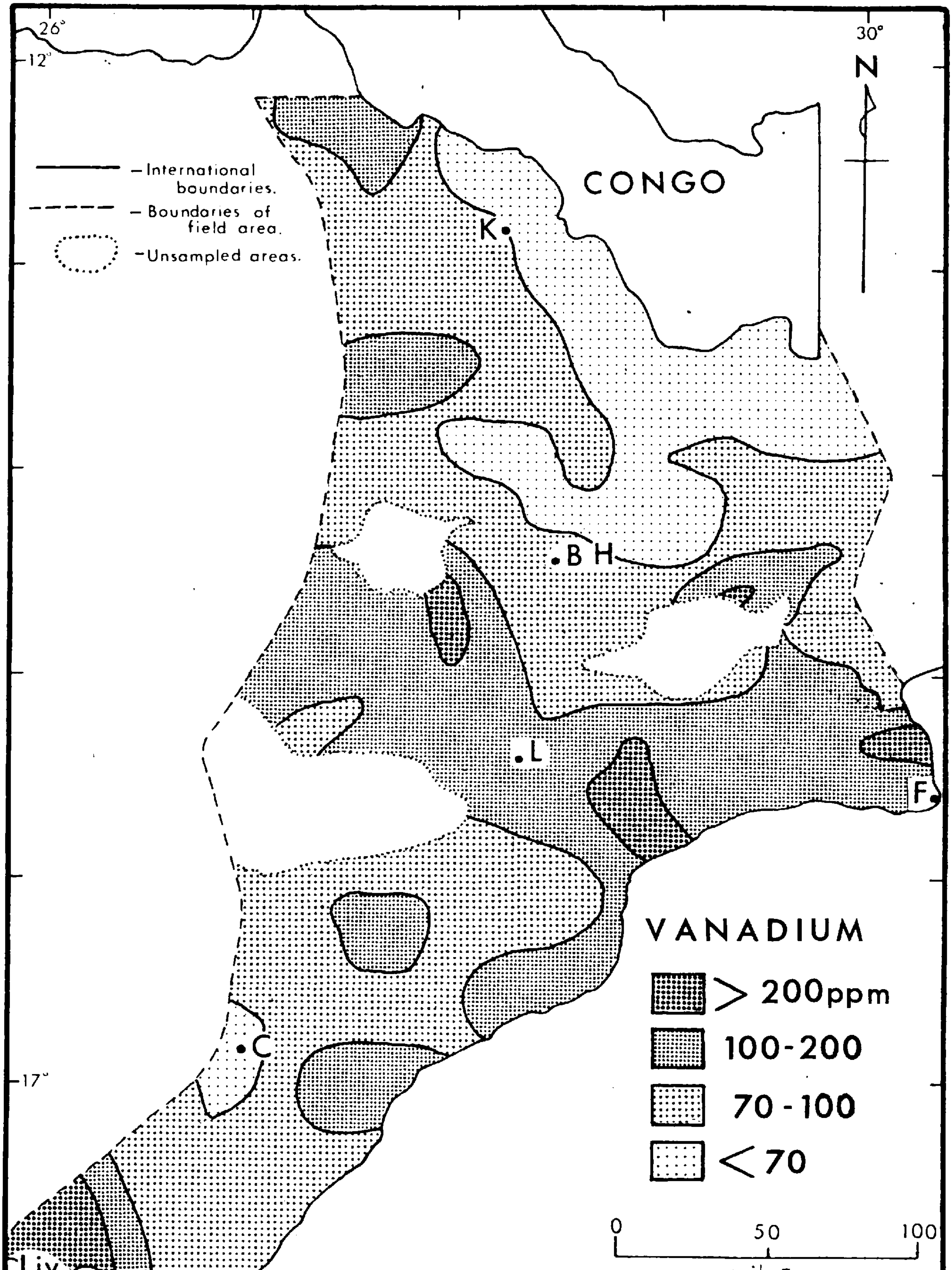

Fig: 21 Vanadium content of drainage sediment.

(j) Nickel background variations (Fig. 22) give very low contrasts. The highest are around Livingstone in the southwest, in the area west and north of Lusaka and south of Lukanga swamp, and in the extreme northwest. There is a low area which parallels the Zambezi escarpment in the southern boundary of the field area.

(k) Chromium background variations (Fig. 23) show a belt of higher values running east and north-west from Lusaka, and an area of high values around Livingstone in the south, and Feira in the east.

(l) Titanium and gallium background variations (Fig. 24, 25) have no particular distinctive trends which can be described.

5.1.2 Implications of minor-element background variations

The main object of defining the minor element background variations in the drainage sediments was to discover firstly if any of the patterns coincided with the metallogenic provinces and secondly to discover whether these are due to variations of metal content in all the rock units within a metallogenic province.

From the above description and figures it is apparent that there are enhanced minor element values in most of the metallogenic provinces or districts described earlier (Fig. 3). These include:

(a) enhancement of copper background in the Copperbelt copper province and Lusaka East copper metallogenic belt and with some enhancement at the northwest end of the Mwinilunga to Broken Hill belt of copper mineralisation;

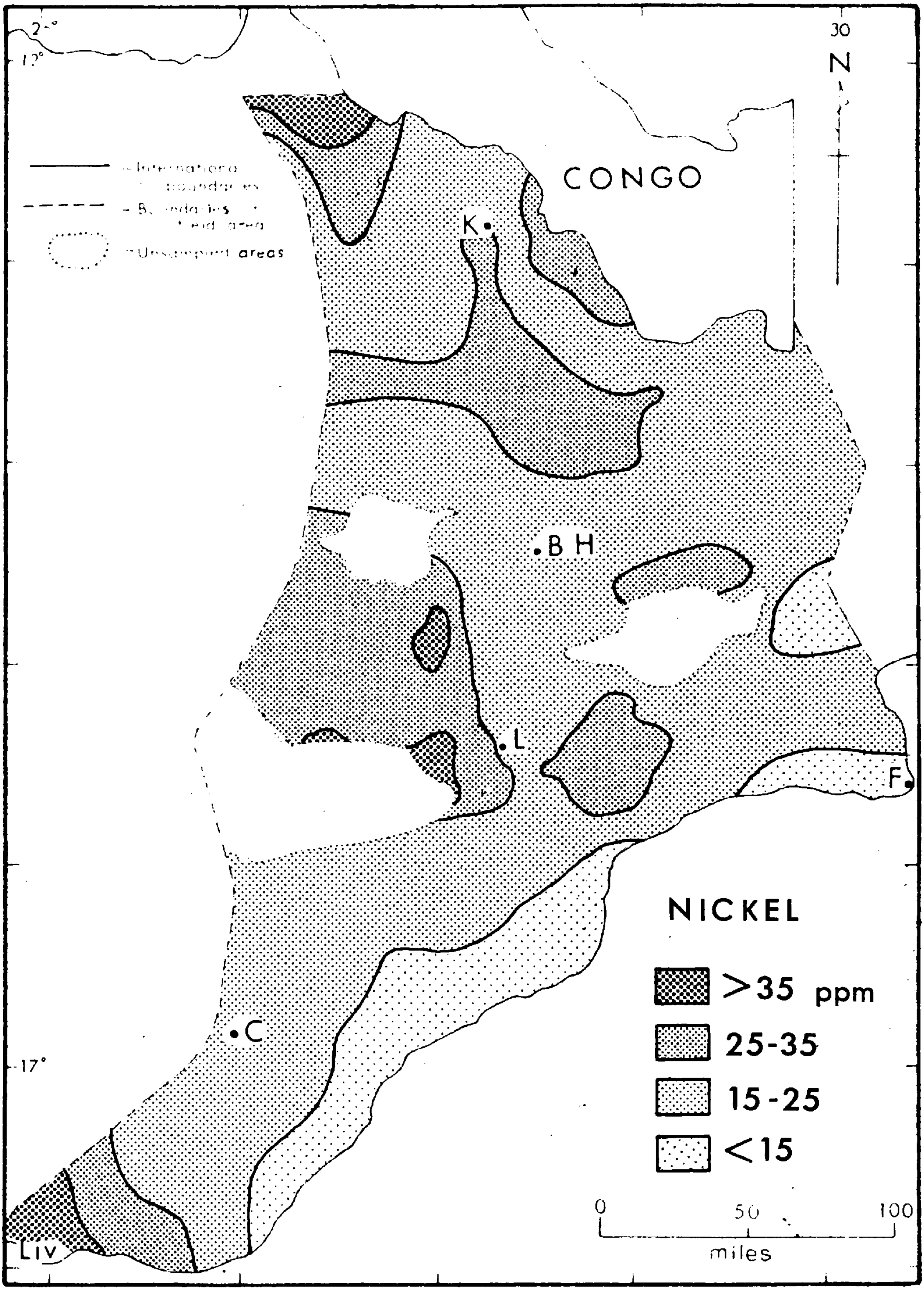

Fig: 22 Nickel content of drainage sediment.

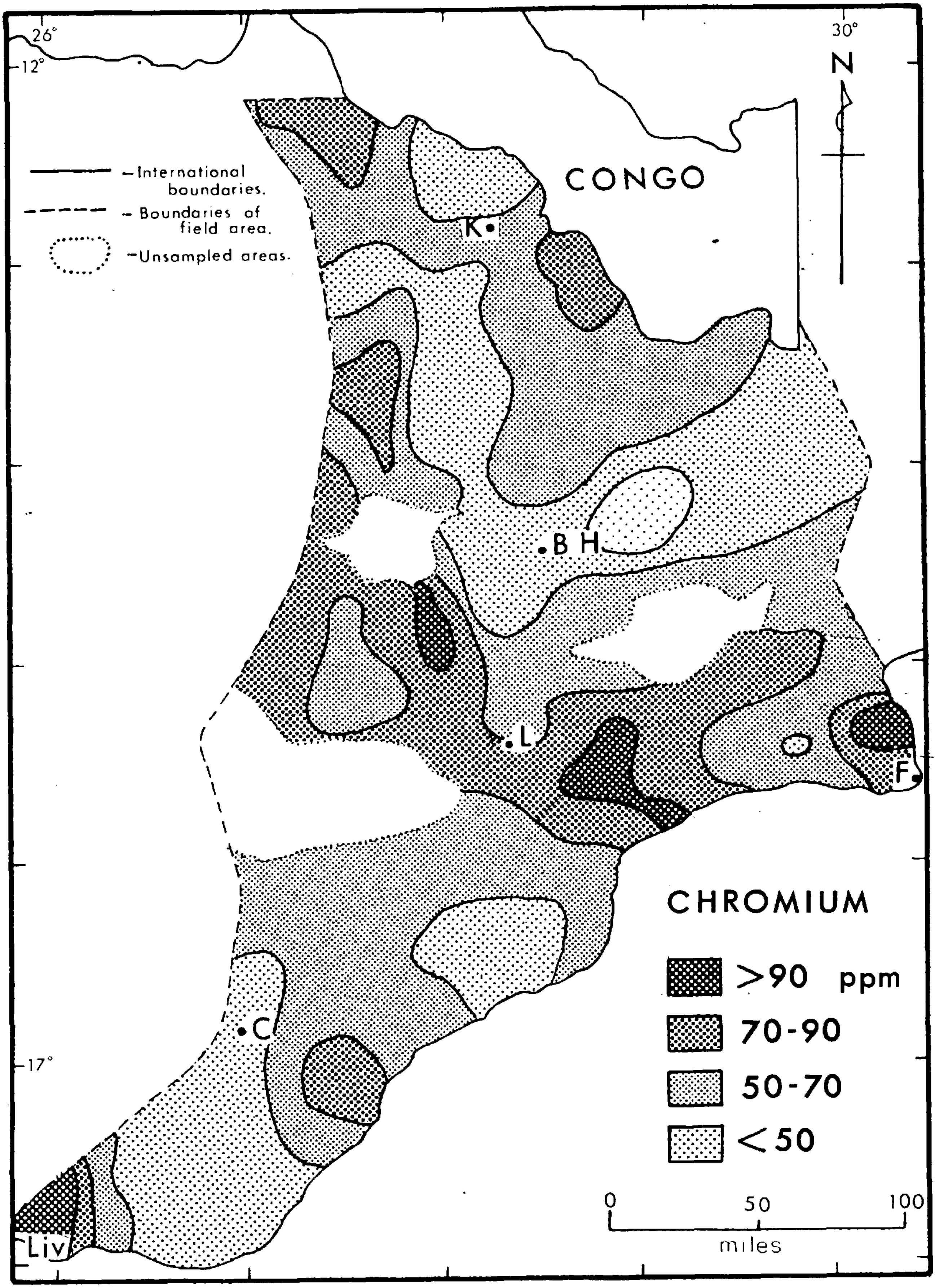

Fig: 23 Chromium content of drainage sediment.

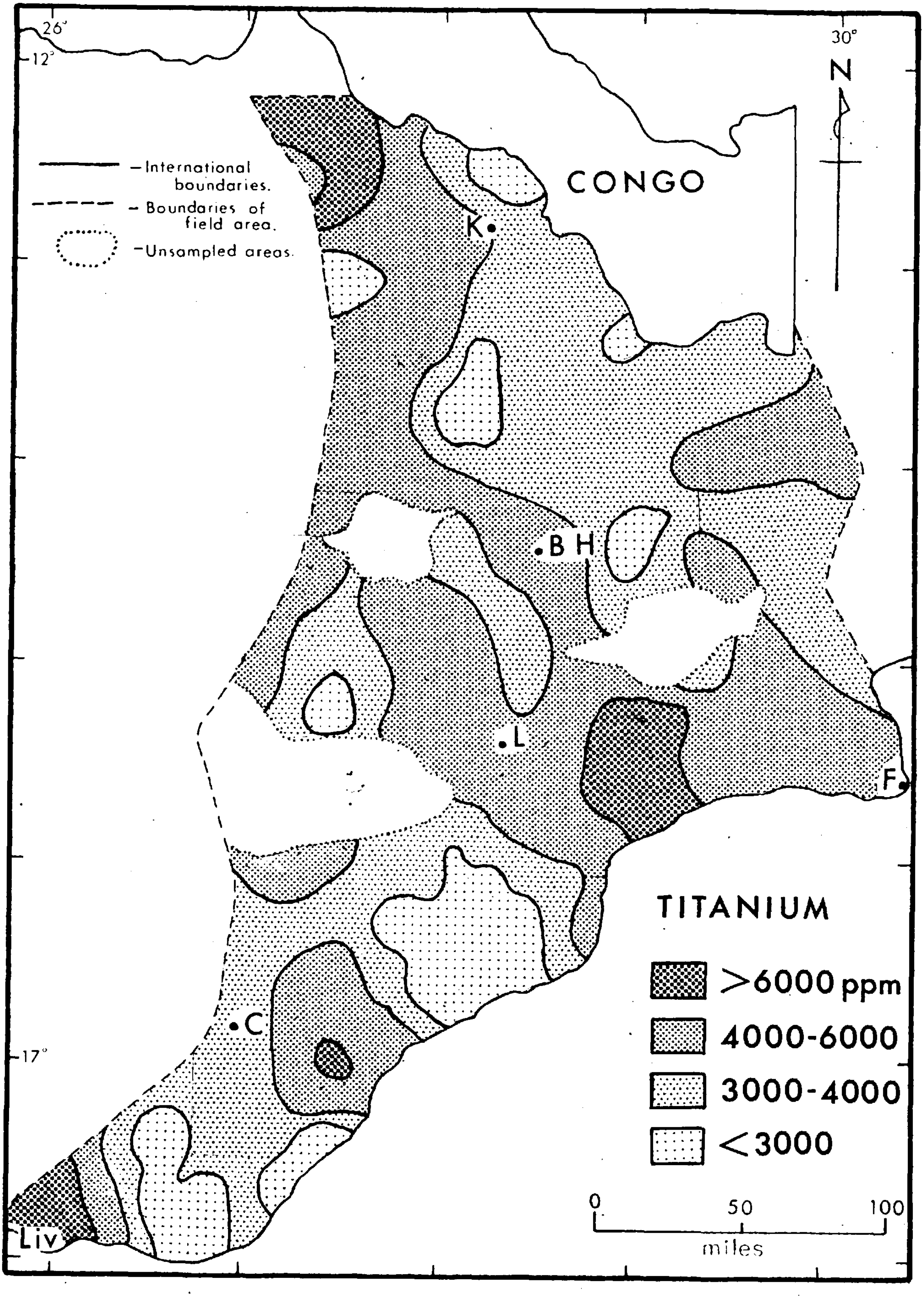

Fig: 24 Titanium content of drainage sediment.

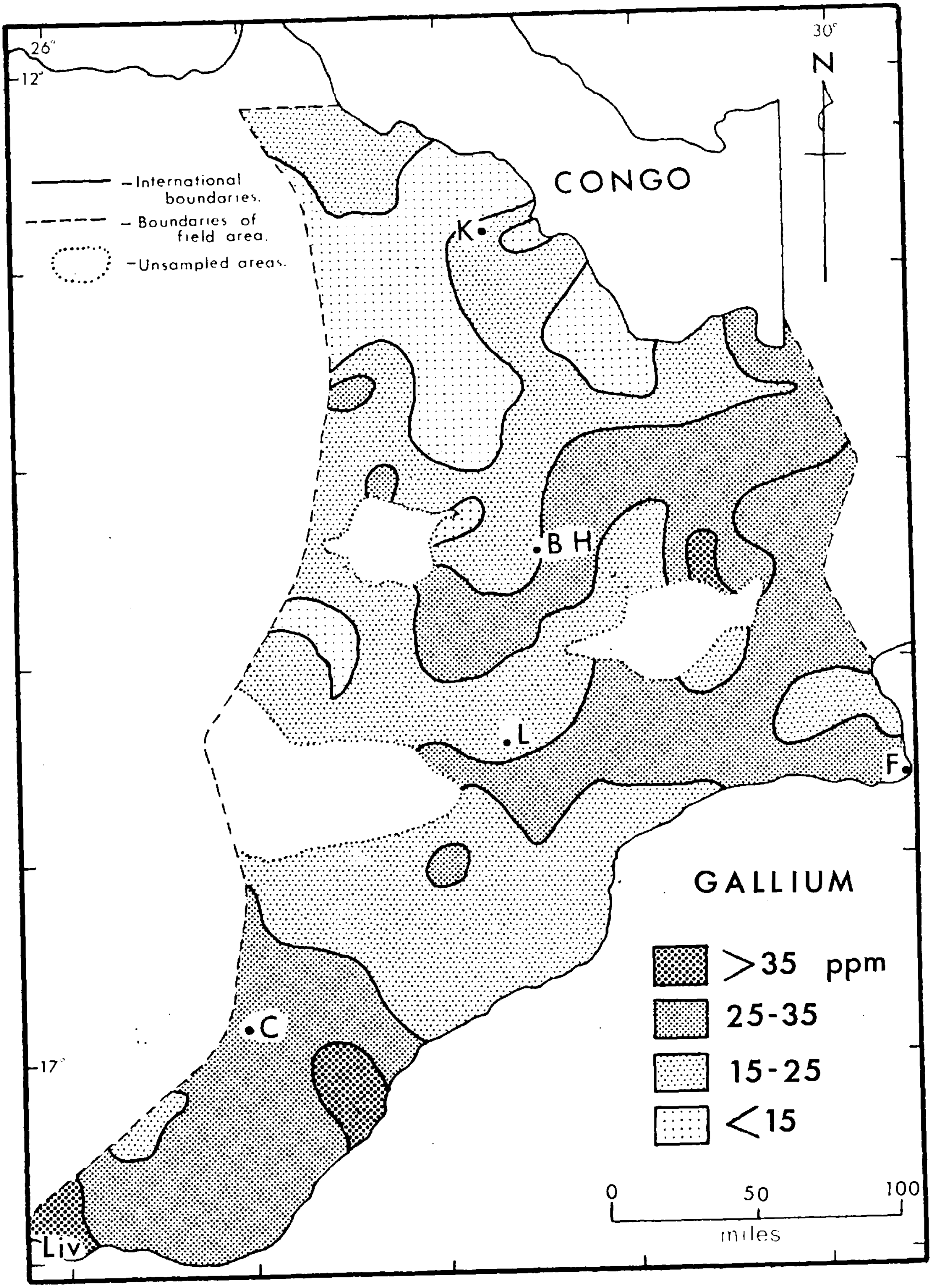

Fig: 25 Gallium content of drainage sediment.

(b) high tin background values in the Choma tin belt; and

(c) increased strontium content in the Feira carbonatite area. The only exception is the lack of a lead or zinc enhancement in the Broken Hill area.

In order to establish these relationships with any degree of certainty it must be shown that these minor-element patterns are not due to other primary and secondary features and, as a corollary, in an unknown area it must be possible to have some system of differentiating minor-element patterns resulting from metallogenic provinces and other primary and secondary features such as:

(a) the prevalence of specific rock types within an area which might give rise to minor element patterns characteristic of that rock type;

(b) the inclusion of highly anomalous samples in the computation of moving-averages which might give rise to enhanced moving-averages, but is not reflected in a general background increase in other samples;

(c) apparent higher element background levels resulting from the increased incidence of minor occurrences of mineralisation somewhere upstream from the sample point giving rise to what will be termed in this thesis 'low order anomalies'; and

(d) the redistribution and concentration of elements in certain secondary environments.

5.1.3 Discussion of relation of minor-element background patterns to metallogenic provinces and districts

(i) Copper metallogenic provinces and districts

The prevalence of certain rock types with characteristic minor-element values is one of the most likely causes of regional minor-element background variation. From a consideration of the mean minor-element contents in stream sediments draining some different geologic units (Table 9), it is clear that basic rocks have two fold higher copper values than other rock types. However, basic rocks also have about a two fold increase in iron, gallium, manganese, vanadium and zinc and about a 1.5 fold increase of nickel, cobalt and chromium compared to stream sediments draining other lithologies. Therefore, if the enhanced copper background patterns were due simply to the increased incidence of basic rocks, these other elements would be enhanced in the same areas.

The high copper background area in the Copperbelt is not associated with enhanced levels of these other elements. Cobalt, chromium and nickel tend to be higher around the enhanced copper background area but not within this area. This strongly suggests that the higher copper background in the Copperbelt area is due to increased levels of copper within the rocks as a whole in a copper metallogenic province. This conclusion is supported by variations in the mean minor-element contents of stream sediments draining different lithologies in different areas (Table 10). (N.B. the area names refer to those defined in Figure 26. Their boundaries were selected on the basis of the main features which were to be defined). The mean copper content of stream sediments draining basement granite and gneiss elsewhere (Table 10(a)). This enhancement of copper is not reflected in stream sediments draining Katangan rocks (Table 10 (b)). This discrepancy is due to there being too few streams, uncontaminated by mining activity, draining Katangan units within the true Copperbelt and in particular the area of high copper background defined by the moving average map. The stream sediment samples used for this calculation (Table 10(b)) were,therefore, of necessity those which

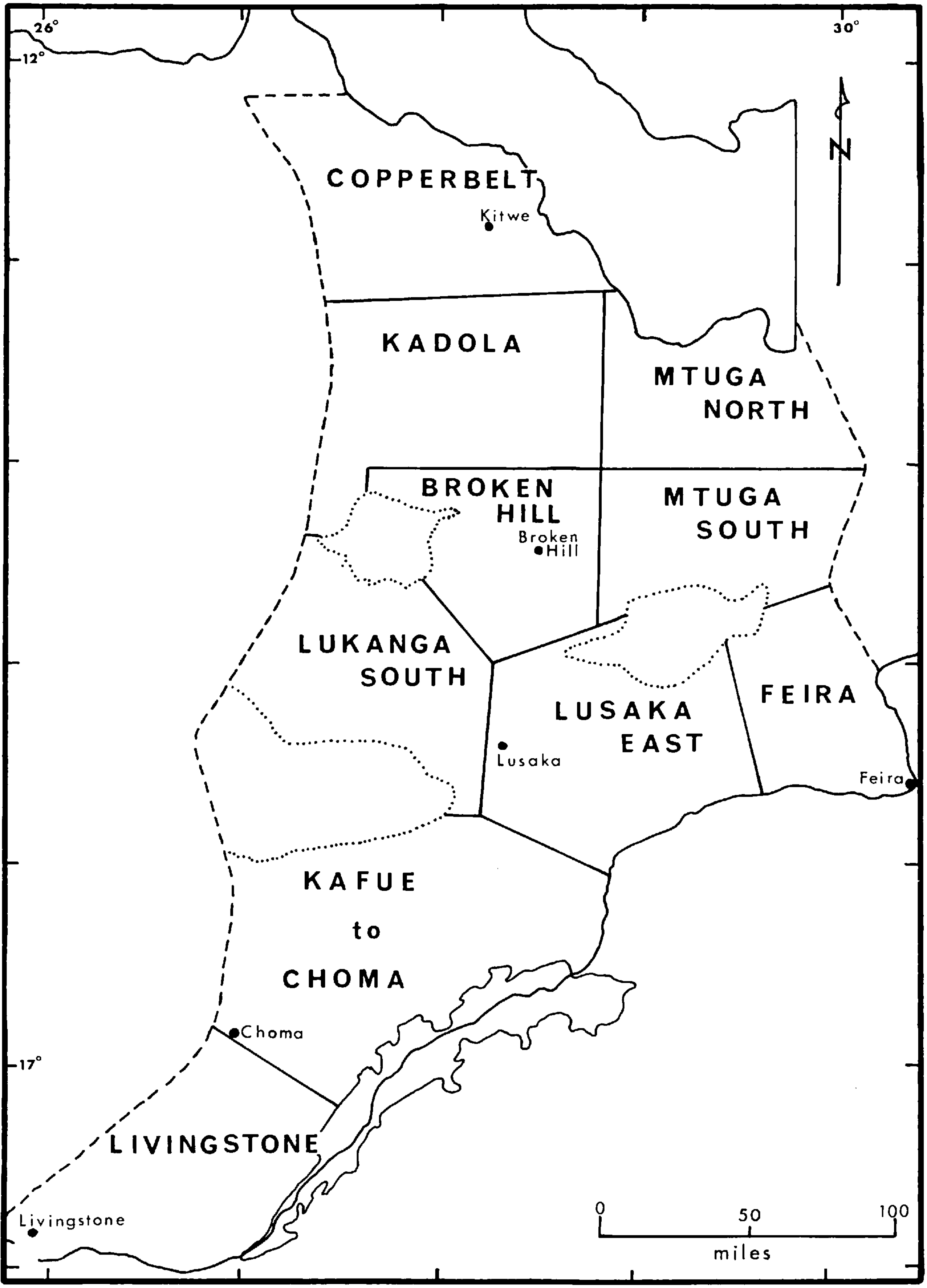

Fig: 26 Field area showing location of regions referred to in tables and text.

Element	Basement Complex			Katangan System		
	Gneiss and granites	Basic rocks	Quartzites and siliceous schists	Lower Roan siliceous	Carbonates	Schists and siliceous schists
Co	30	50	35	35	45	35
Cr	50	80	65	65	75	60
Cu	35	80	40	30	45	30
Fe_2O_3	4%	12%	3%	5%	5%	3%
Ga	25	40	17	20	19	14
Mn	290	710	180	370	280	130
Ni	35	60	45	40	50	40
Pb	35	25	15	20	16	14
Sn	5	5	5	4	4	5
Sr	96	94	96	96	121	104
Ti	4000	7250	3400	3920	4820	4160
V	80	270	80	115	140	110
Zn	80	150	75	80	55	50
No. of samples	142	12	22	106	52	57

N.B. All mean values are geometric in ppm.

Table 9: Mean minor-element contents of stream sediments draining different lithologies.

(a) Basement granites and gneisses

Areas Elements	Livingstone Choma	Mazabuka	Lukanga South	Broken Hill & Kadola	Copperbelt	Lusaka East	Mkushi South	Mkushi North
Co	30	35	30	40	30	40	20	30
Cr	45	60	55	65	40	70	35	45
Cu	20	35	30	40	65	50	20	25
Fe_2O_3	4%	5%	4%	3%	2%	6%	3%	2%
Ga	30	30	30	20	10	35	30	25
Mn	360	500	290	130	110	520	290	220
Ni	30	40	35	45	30	35	25	30
Pb	45	45	40	30	10	40	30	40
Sn	6	5	5	4	4	5	5	4
Sr	100	95	90	90	90	96	91	90
Ti	3590	4830	4490	3550	2870	5450	3510	3730
V	80	100	90	60	50	150	70	65
Zn	85	100	80	55	50	110	75	90
No. of samples	39	41	30	18	27	34	17	23

N.B. All mean values are geometric in ppm.

Table 10: Mean minor-element content of stream sediments draining different geologic units in different areas

Areas / Elements	Arenaceous facies: Mazabuka	Kafue	Lukanga South	Broken Hill	Kadola	Copperbelt	Mkushi North	Carbonate facies: Kafue	Lukanga South	Kadola	Copperbelt
Co	35	40	30	40	40	40	25	50	45	40	40
Cr	55	70	65	65	75	55	20	90	120	45	55
Cu	30	35	35	25	25	35	10	60	55	30	40
Fe_2O_3	7%	5%	4%	2%	2%	2%	3%	8%	8%	3%	2%
Ga	20	20	20	15	12	13	35	30	35	11	6
Mn	470	450	270	110	80	80	110	570	340	120	70
Ni	35	40	40	60	55	40	25	50	70	45	35
Pb	40	15	12	19	30	13	30	8	35	20	17
Sn	4	4	5	4	4	4	4	4	5	4	4
Sr	90	105	95	90	110	120	110	90	120	140	90
Ti	3770	4250	3850	4930	3610	4190	3450	5830	5940	2680	4500
V	110	140	120	80	65	95	95	170	220	110	65
Zn	135	80	50	65	40	55	60	50	75	40	40
No. of samples	20	60	39	6	14	16	6	16	9	12	5

(N.B. all mean values are geometric. Units in ppm.)

Table 10(b): Units of the Katangan System which drained the Katangan units in the north and west of the area defined as the Copperbelt in figure 26 and are not representative of the area as a whole, or the copper-rich area in particular.

The high copper background in the Lusaka metallogenic belt, on the other hand, is more intimately associated with enhanced cobalt, nickel and chromium values. (See Figs. 12, 14, 22, 23) This association of elements high in mafic minerals suggests that increased incidence of basic rocks is the reason for the higher copper background in the Lusaka area. This conclusion, however, is not entirely supported by the relatively high mean copper value of 50 ppm of stream sediments draining Basement granite and gneiss in the Lusaka East area (Table 10(a)). Similarly, high mean copper values occur in streams draining Katangan carbonate facies in the Kafue and Lukanga South area to the west of Lusaka (Table 10(b)). Most of the Katangan carbonate rocks occur in the northeast of the Kafue area (Fig. 26), and are included in the 20-30 ppm copper contours shown on figure 12.

The high copper background area just north west of Lukanga Swamp coincides with the Broken Hill to Mwinilunga metallogenic belt. However, enhanced cobalt, chromium, nickel, vanadium and ferric oxide background patterns are associated with it, which suggests that underlying basic rocks are present. Therefore, the copper high background cannot be shown to be due purely to the metallogenic zone.

The second possible reason for increased copper background patterns is the inclusion of highly anomalous values in the moving-average computation. This appears to be a minor source of interpretative error; firstly because the extraction of all values over a threshold copper value of 96 ppm prior to the calculation of the moving-average has not changed the overall copper background variations (Fig. 13), and secondly when histograms (Fig. 27) are plotted of the element values of samples in the different areas defined in Fig. 26 it can be seen how the mode for copper increases in the Copperbelt and Lusaka East area from the 7-15 ppm, to the 15-30 ppm class interval. If just a few very high copper values were giving the increased background then these changes of mode would not be evident. The copper distributions of both the Copperbelt and Lusaka East are statistically significantly higher than the Broken Hill values at the 99% probability level according to Kolmogorov-Smirnov test for non-parametric data (miller and Kahn, 1962).

A third possible reason for increased copper background patterns is the inclusion of what might be termed 'low order anomalies'. That is to say, the occurrence of mineralisation within the catchment area of the sampled drainages, but with copper values diluted by distance between the sample point and the mineralisation, which give rise to slightly increased values rather than highly anomalous values. Although samples were never taken downstream of known mineralisation or contamination this is a possible explanation. However, catchment sizes were mostly small, and since it is not likely that mineralisation will always be at the upstream end of a catchment area from a sample point, it would seem reasonable to expect a considerably greater number of highly anomalous samples than have been found if this were the reason. If, however, increased frequency of these low order anomalies were the reason for the enhanced copper background in the copper metallogenic provinces, it would not detract from this provincial geochemical reconnaissance method as a means of locating metallogenic provinces. It would simply mean that the increased copper background in the drainage sediment was not due to a similar increase in the surrounding bedrock.

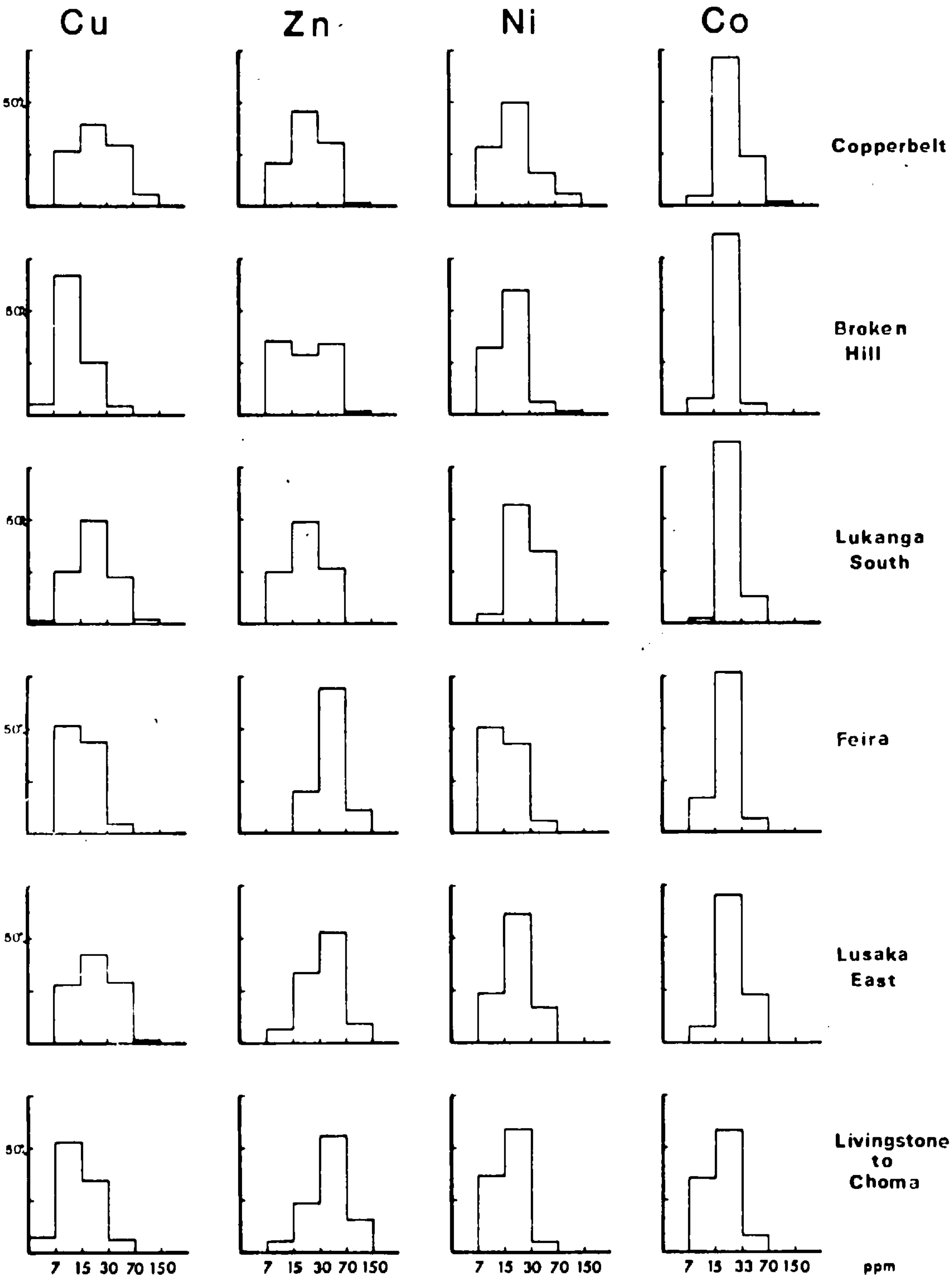

Fig: 27 Frequency distributions of minor element values in different areas.

The higher content of copper in rocks in the copper metallogenic provinces can only be established by analyses of rock samples. The results of rock analyses will be discussed later.

In conclusion it can be stated:

(a) that the enhanced copper background pattern in the Copperbelt is related to the copper metallogenic province there, and that the higher values are due either to increased incidence of copper mineralisation or, more likely, actual higher copper background values in the rocks of the province as a whole;

(b) that the enhanced copper background pattern coinciding with the Lusaka copper metallogenic belt is possibly due to the increased occurrence of basic rocks, and/or the increased incidence of copper mineralisation, or possibly higher copper background values in the rocks of the district as a whole;

(c) that the enhanced copper background north of Lukanga Swamp coinciding with the Mwinilunga to Broken Hill metallogenic belt is most likely to be due to the increased occurrence of basic rocks as yet unmapped due to deep overburden in that area.

(ii) Tin metallogenic district

Enhanced tin background concides with the known tin mineralisation in the Choma tin belt (Fig. 15). Tin is not enhanced in any particular rock type (Table 9). Therefore the possible explanations for the increased tin values are:

(a) that only a few highly anomalous samples have been included in the moving average computation giving rise to spurious background measurement;

(b) low order anomalies due to increased tin mineralisation;

(c) contamination from old mine workings, or

(d) higher tin background level in the bedrock within the Choma tin belt.

Although sediments from streams draining known tin mineralisation or contamination were not sampled, it was not possible to say for certain whether all the sampled streams were not contaminated, since there are many small tin pegmatite showings worked by indigenous miners which are probably not mapped. For this reason, the two highest tin values of 85 and 160 ppm were eliminated on the basis of being possibly due to contamination. Despite neglecting these samples, out of the 40 samples which occur within the tin belt, 20 of them give tin values greater than or equal to the detection limit of 5 ppm, of which 13 are greater than 5 ppm. The values range mostly between 6-20 ppm with one sample at 40 ppm. In an area of comparable size over similar Basement schists such as occur within the tin belt, one sample out of 40 is above the detection limit. This increased incidence of tin values is statistically significant at the 99% probability level according to the Kolmogorov-Smirnov test for non-parametric data. It indicates that the moving average results are not due simply to a few highly anomalous samples.

Whether the pattern is due to low order anomalies, or high tin values in the rocks of the tin belt as a whole, it is impossible to say without the results of rock analyses which will be discussed later. Similarly, the possibility of contaminatin as the cause, although it seems unlikely, is nevertheless possible and can only be disproved with certainty by rock analyses.

(iii) Definition of carbonatite district by strontium background values

Enhanced strontium background coincides with the known carbonatite district of Feira (Fig. 16). Strontium, however is also enhanced in carbonate rock in general (Table 9) (Rankama and Sahama,1949). (N.B. The detection limit of strontium was 100 ppm and the majority of samples which had strontium levels of below that figure, were valued at 90 ppm.) The possible explanations for the increased strontium background value in the Feira Carbonatite district, therefore, are:

(a) that only a few highly anomalous samples have been included in the moving average computation giving rise to a spurious background measurement;

(b) low order anomalies due to increased carbonatite occurrence;

(c) greater prevalence of carbonate rocks;

(d) higher strontium background value in the bedrocks of the carbonatite province.

Sediments of streams known to drain carbonatite intrusions were not sampled. Within a general 900 square mile area around Feira over half (18) of the 31 samples had strontium values above or equal to the detection limit of 100 ppm. Of these, 13 were above the detection limit with a maximum value of 800 ppm and the rest varied between 300 and 400 ppm. In an area of comparable geology 7 out of 38 samples have measurable strontium values, of which only 2 samples are above the detection limit with values of 200 ppm. This difference is statistically significant at the 99% probability according to the Kolmogonov-Smirnov test. This increase in the number of samples with strontium values within the carbonatite district suggests a more general increase in strontium content in the rocks than is implied by the first possible explanation; that is a few highly anomalous samples draining carbonatite outcrop.

Limestone, dolomite or marble have not been mapped or reported in the Feira area despite the good outcrop. Clearly the higher strontium level in this area is not due to the presence of carbonate rocks. The interpretation, however, that high strontium values in areas of unknown geology is necessarily the result of underlying carbonatites, is clearly not a valid conclusion. For example, there is a high strontium background pattern in Kadola area overlying 350 square miles of Kundelunga carbonate rocks. Five out of the 9 samples in the area have strontium values greater than or equal to the detection limit, and 4 of these 5 samples have values of 200, 200, 600 and 800 ppm. These values are comparable to strontium values of samples draining the carbonatite district.

In conclusion, therefore, it can be said that the high strontium background in the Feira carbonatite district is due either to low order anomalies or higher strontium background values in all the bedrock. In order to interpret strontium background patterns in areas of unknown geology, however, it is necessary to use other elements, in addition to strontium, as tracers for carbonatites. This conclusion supports Deans' and Powells' (1968) work in which they suggest that phosphorous, barium, yttrium, lanthanum, cerium, niobium in addition to strontium should be analysed, if certain identification of carbonatites is to be made, and useful conclusions as to their mineral potential are to be drawn.

(iv) Lead and zinc metallogenic district at Broken Hill

No enhanced background of lead or zinc was noted in the Broken Hill area. This is probably due partly to geographical features which made it impossible to sample in an area of over 100 square miles around Broken Hill. The mine lies on a very broad catchment divide with very few issuing dambos or streams, and those are contaminated by mining and smelting activities. Later analysis of carbonate rock samples from the Broken Hill area showed a considerable increase of about 2-3 times background lead and zinc compared to rocks elsewhere. These rocks with enhanced background levels probably extend for some 20 square miles around the mineralisation (Colvine, pers. comm.). It would appear that Broken Hill lead and zinc is of fairly limited occurrence which does not qualify even as a metallogenic district on the basis of areal extent.

5.1.4 Relation of minor-element background patterns to lithology

The influence of differing lithology on the minor element background patterns has already been mentioned in order to relate the copper and tin background patterns to metallogenic provinces or districts. The mean element values of stream sediments draining single lithologies (Table 9) show the most obvious variations, and interpretation of some of the minor-element background patterns, defined by the moving average technique, can be made on the basis of prevalent lithologies in certain areas.

It has been noted in the description of the background patterns that all the elements except lead and tin are greatly enhanced in value in the south west corner of the field area around Livingstone. These high values are due to the Karroo volcanic basalts which mantle the area. The values are probably also increased by the accumulation of the elements in the high pH conditions of the secondary environment overlying these basic rocks.

Most of the elements, with the exception of lead, tin and strontium, tend to be enhanced in the stream sediments draining the basic volcanic and intrusive units of pre-Karroo age associated with Basement and Katangan units (Table 9). These basic units, however, do not outcrop extensively enough to give significant regional minor-element patterns; although their increased occurrence in certain areas might have given rise to slightly enhanced background values. Areas where this was thought to have happened have already been mentioned in the discussion of the relationship of copper with the copper metallogenic provinces and districts.

The zinc background variations show very distinct regional distributions in sympathy with the geology (Fig. 17). The areas with background values over 30 ppm which occur in the east and south west of the field area correspond very closely with the areas of Basement outcrop, whilst the north and west of the field area, of below 30 ppm background zinc, corresponds with the outcrop of Katangan units. The reason for this distinctive variation is not entirely clear. The most reasonable explanation is probably the increase in biotite and prevalence of biotite schists in the Basement units compared to the Katangan units. Of the rock-forming minerals biotite tends to hold the most zinc (Rankama and Sahama, 1949). The mean zinc values of the different rock units (Table 9) confirms the higher zinc in the stream sediments draining the Basement rocks compared to the Katangan System carbonates and overlying schists and siliceous sediments. The Lower Roan Katangan sediments, however, have a zinc value comparable with the Basement rocks. This is probably due to:

(a) the fact that the Lower Roan unit immediately overlies the Basement and is generally arkosic in composition and would, therefore, in general reflect the minor-element composition of the Basement rocks, and

(b) because the Lower Roan formation tends to have a narrow surface outcrop, and the geological control is poor on the small scale maps used for selecting the samples of streams draining single geologic units. It is, therefore, possible that at least some of the samples chosen as draining the Lower Roan formation alone also drained the underlying Basement units.

Lead values are considerably increased in the stream sediments draining Basement Granites and gneiss (Table 9). The distribution of the enhanced lead background patterns (Fig. 18) corresponds well with the extensive areas of granitic outcrop and not to the Basement area in general as does zinc. This would be expected from a consideration of lead contents in different rock types, since granites and acid igneous rocks tend to have from 20-30 ppm lead compared with other rock types with 5-9 ppm (op. cit.).

The affinity of strontium for carbonate rocks in the Kadola area as well as carbonatite rocks has already been mentioned. It is interesting to note that strontium is also very high in streams draining the Karroo basalts around Livingstone. This seems to suggest a probable high calcium content for these rocks, since strontium typically replaces calcium in igneous rocks (op. cit.) and a possibly similar genesis to the carbonatites near Feira. Since they both occur along rift zones this seems likely.

In conclusion, therefore, it may be said that most of the element distributions, with the possible exception of tin, are likely to be affected to somedegree by differing lithologies. Interpretation of background element variations as reflecting metallogenic provinces or districts can, therefore, only be made if the effects of varying lithologies have first been eliminated as a possible explanation.

5.1.5 Relation of minor element background patterns to the secondary environment

The most obvious secondary environmental difference of stream sediments is between the dambo sediments on the plateau and the sandy stream sediments in the escarpment areas. Since the clays in the dambo sediments tend to absorb and concentrate minor elements, and since this is the fraction most washed from sandy stream samples, it was thought likely that the greatest contrasts of minor element contents due to the secondary environment would be caused by this difference of sample type. Nickel is the only element which appears from its regional background distribution to be affected by this feature (Fig. 22), since there is a strip of low nickel background values paralleling parts of the escarpment area. To examine further the significance of this feature samples were classified on the basis of the two main sample types. They were selected from adjacent areas of similar Basement geology so as to minimise the effect of variations due purely to geology. The means and single standard deviation ranges of these two groups of sample type were then calculated (Table 11). These results show a slight decrease of mean value for Co, Cu, Ni, Pb and Zn in the escarpment sand type of sample as compared to the dambo sediment sample. These differences of between 5% for Pb and Co to 30% for Cu tend to be lower than variations due to the primary features described in the previous two sections. Therefore, sediment type does not appear to be a dominant reason for minor element variation. This conclusion supports the evidence from the moving average maps of the elements, which with the exception of nickel, do not show depressed background values in the escarpment areas, and evidence

Secondary Environment		No. of samples	Co	Cu	Ni	Pb	Zn
Sand sediment in escarpment areas	GM* Range+	121	20 . 13-29	14 8-25	17 11-25	20 15-27	40 24-67
Grey, clay-rich dambo type of samples in plateau drainages	GM Range	117	21 14-34	19 10-36	21 14-31	21 17-26	45 28-73

*Geometric mean
+Single standard deviation range

Table 11: Mean element content and standard deviation ranges of different stream sediment types.

from the Namwala area (Webb et al, 1964) where only small variations of minor-element value, with sample type were noted.

The manganese and ferric iron distribution indicates a considerable increase in the southern half of the field area (Figs. 19-20). These 2-3 fold increases of background value do not appear to correlate with any known geological feature. These patterns do, however, correlate fairly closely with rainfall distribution (Fig.4), which is nearly one half in the south what it is in the north, and to a lesser extent with the soils (Fig. 5). In an attempt to evaluate the secondary environmental features responsible for this variation, frequency distributions of manganese values in wet and dry drainage of different types over three different areas have been drawn (Fig. 28). The general tendency of manganese values to be higher in dry drainage sediments and in particular dry sand sediments in the south of the field area is shown in these histograms. This enhancement of manganese in drier drainages and drier parts of the country is probably the result of the greater evaporation in the south due to lower rainfall and a lower number of rainfall days per year. This results in a greater amount of oxidation of Mn^{+2}, which is in solution, to Mn^{+3} and Mn^{+4} which are insoluble manganic hydrates ($Mn\ (OH)_3$) and pyrolusite ($Mn\ O_2$) respectively (Vinogradov, 1959). In addition, the higher rainfall and longer rainy season in the north results in a greater amount of leaching of manganese in the soluble Mn^{+2} form. These conclusions are reinforced by the higher manganese values in wet and dry streams compared to the dambo sediments in both the Kafue to Livingstone area and Lusaka to Feira area. They also agree with the conclusions on the dispersion of manganese in the secondary environment in North Wales, where manganese was found to migrate easily in the groundwater

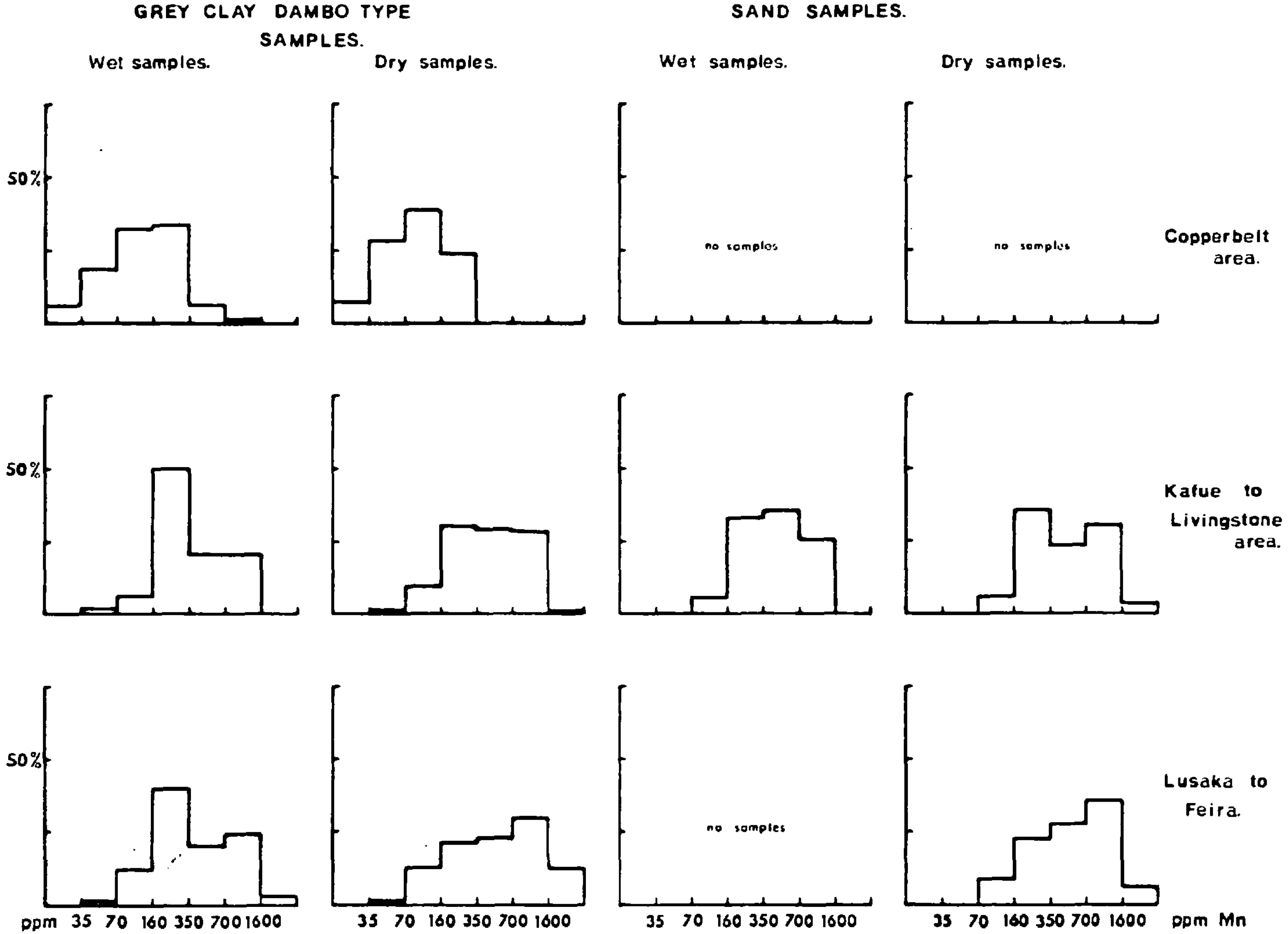

Fig: 28 Frequency distributions of Manganese content in different sample types in different areas.

of the acid moorland environment, which might be thought of as equivalent to a dambo type of environment in Zambia, but is quickly precipitated in the open aerated streams where evaporation takes place, and the soluble Mn^{+2} is oxidised to insoluble Mn^{+3} (Horsnail, 1968). This explanation also agrees with findings in Hawaii, which showed that MnO_2 accumulates in soils by precipitation during the dry season in tropical areas of seasonal rainfall (Sherman, 1949). Presumably essentially the same process is affecting the relative iron content in the drier and wetter areas of Zambia.

In conclusion, therefore, manganese and to a lesser extent ferric iron background distributions are modified by the rainfall distribution, and the type of drainage sediment. Other elements do not appear to be affected at all by the rainfall distribution. There are minor decreases of element value in sand stream samples compared to clayey dambo type samples. Nickel is the only element, however, which appears to have had its regional background significantly modified by this feature.

5.2 R-MODE FACTOR ANALYSIS OF THE MINOR ELEMENT DATA FROM PROVINCIAL DRAINAGE SEDIMENT SAMPLES

5.2.0 Introduction

In the previous section describing the background patterns and their relation to the geology and secondary environment, certain associations have become apparent. The most obvious of these associations is related to the Karroo basalts over which all the elements, with the exception of lead and tin, have enhanced values, and in particular cobalt, nickel and chromium. In addition, lead and zinc are enhanced in Basement areas, manganese and ferric iron are enhanced in the drier southern half of the region. Similarly, the mean minor-element contents of streams draining different lithologies (Table 9) indicate other possible element associations not recognised by the evaluation of the background distribution. For example, practically all the elements, with the exception of lead, tin and strontium, are enhanced in the Basement basic rock units; lead is enhanced in the Basement granites, and strontium is enhanced in the Katangan carbonates. It can also be reasonably expected that there are other element associations which are related more to lithological differences in composition than to the largely stratigraphic divisions on which the geologic units mentioned in the table have been based. These various associations suggest that at least some of these minor elements which appear to be regionally correlated might more easily be described as a single parameter. This single parameter of associated elements would in turn be simpler to relate to the features controlling the element variations. R-mode factor analysis was therefore used to first clarify the minor element associations. After selecting a suitable set of associations, R-scores for each factor (association) were calculated, plotted and contoured in order to show the areal distribution of the controlling features.

Analyses of thirteen elements were used in the factor analysis computation namely, Co, Cr, Cu, Ga, Fe_2O_3, Mn, Ni, Pb, Sn, Sr, Ti, V and Zn.

5.2.1 Choice of number of factors

Because most of the element frequency distributions had a general lognormal form, the data was transformed to the log base 10 in order that their frequency distributions more closely approximate a normal gaussian form and therefore the product moment correlation coefficients be statistically more meaningful. The correlation coefficient matrix to be factored (Table 12) shows that practically every element with the exception of lead, strontium and tin have statistically significant correlations with almost every other element. Taking an arbitrary correlation coefficient of 0.7 and greater, two distinctive associations are formed, namely: V-Fe_2O_3-Mn and Ni-Cr-Co. Reducing this level to 0.6, Ti-V-Cr are added to the former association and Cu to the latter. Cr now appears in both associations making it difficult to interpret them separately. The lower the correlation coefficient the more difficult it is to define the elements into distinctive associations. R-mode factor analysis overcomes this problem.

This correlation coefficient matrix was factor analysed with unities in the principal diagonal using the 'Promax Oblique primary pattern matrix' for extracting from 3 to 12 factors (associations). The Varimax orthogonal rotated solution was powered by 2 to give the Promax oblique rotation. Powering up to 4 was tried but the associations remained the same although the differences between high and low loaded elements increased. Therefore, the oblique matrices powered by 2 were chosen. The associations of minor-elements extracted are listed in table 13. Only elements with factor loadings of 0.3 or greater are listed in this table although every element is given a loading for each factor. This arbitrary level of significant loading value was selected on the basis of element variations with R-score variation and will be discussed more fully later (Section 5.2.2). In the actual factor matrix, some associations have the majority of elements high negative loadings. These negative loadings are the

	Ti	V	Cr	Mn	Fe_2O_3	Co	Ni	Cu	Zn	Ga	Sr	Sn	Pb
Pb	0.15	0.07	0.08	0.24	0.10	0.07	0.01	-0.01	0.24	0.39	-0.01	0.13	1.0
Sn	0.09	0.10	0.03	0.10	0.07	0.04	0.03	0.04	0.08	0.16	0.0	1.0	●
Sr	-0.07	0.15	-0.07	0.15	0.13	-0.06	-0.04	0.01	0.11	-0.06	1.0		
Ga	0.52	0.52	0.47	0.40	0.50	0.41	0.38	0.38	0.31	1.0		●	●
Zn	0.26	0.35	0.28	0.45	0.48	0.26	0.21	0.28	1.0	●	●	•	●
Cu	0.43	0.48	0.53	0.24	0.42	0.56	0.57	1.0	●	●			
Ni	0.44	0.51	0.66	0.13	0.36	0.71	1.0	●	●	●			
Co	0.50	0.53	0.56	0.27	0.46	1.0	●	●	●	●			•
Fe_2O_3	0.55	0.75	0.53	0.69	1.0	●	●	●	●	●	●	•	●
Mn	0.39	0.52	0.31	1.0	●	●	●	●	●	●	●	●	●
Cr	0.58	0.65	1.0	●	●	●	●	●	●	●	○		•
V	0.64	1.0	●	●	●	●	●	●	●	●	●	●	•
Ti	1.0	●	●	●	●	●	●	●	●	●	○	●	●

● or ○ above 0.081 which is significant at the 99% level

• or ○ above 0.069 which is significant at the 95% level

(number of samples 1159)

Table 12: Correlation coefficients of minor elements from provincial reconnaissance data

Factor Model	3	4	5	6	7	8		9	10	11	12
Factors											
1	Ni .9 Co .8 Cr .8 Cu .7 Ti .6 V .6 Ga .4 Fe*.4 Sr- .3	Ni .9 Co .8 Cr .8 Cu .7 Ti .6 Fe .4 Ga .4	Ni .9 Co .8 Cu .8 Cr .7 V .4 Ti .4 Ga .3	Ni .9 Co .8 Cu .8 Cr .6 V .4 Ti .3 Ga .3	Ni .9 Cr .8 Co .7 Ti .5 V .5 Cu .3	Co .8 Ni .8 Cr .4	16.2	Ni .9 Co .8 Cr .5 V .3	Co .9 Ni .7	Co .9 Ni .7	Cr .8
2	Mn .7 Sr .7 Fe .7 Zn .6 V .5	Mn .8 Fe .7 Zn .7 V .5 Sr .4 Ga .4 Pb .4 Ti .3	Mn .9 Fe .9 V .6 Ti .5 Zn .5 Ga .4 Cr .3	Fe .8 Mn .8 V .7 Ti .7 Ga .4 Cr .4	Mn .8 Fe .8 V .6 Ti .6 Ga .4 Cr .3	Mn .9 Fe .6 V .3	13.6	Mn .9 Fe .7 V .4	Mn 1.0 Fe .7 V .4	Mn .9 Fe .3	V .8 Fe .7
3	Pb .8 Ga .5 Sn .5 Sr -.4	Pb .6 Ga .4 Sr -.6	Pb .9 Ga .4 Zn .4	Pb 1.0 Ga .5	Pb .9 Ga .5	Pb 1.0 Ga .5	9.4	Pb 1.0 Ga .3	Pb 1.0	Pb 1.0	Pb 1.0
4		Sn 1.0	Sn 1.0	Sn 1.0	Sn 1.0	Sn 1.0	7.8	Sn 1.0	Sn 1.0	Sn 1.0	Sn 1.0
5			Sr .9	Sr 1.0	Sr 1.0	Sr 1.0	8.0	Sr 1.0	Sr 1.0	Sr 1.0	Sr 1.0
6				Zn .9 Mn .4 Fe .3	Zn .9	Zn .9	7.8	Zn .9	Zn 1.0	Zn 1.0	Zn 1.0
7					Cu .8	Cu .8 Ga .3	7.2	Cu .8	Cu .9	Cu .9	Cu .9
8						Ti .8 Cr .6 V .6 Ga .6 Fe .4	18.4	Ga .8 Cr .4 V .3	Ga .9	Ga .9	Ga .9
9							% correlation explained by each factor association	Ti .9 V .3 Cr .3	Ti .9	Ti .9	Ti .9
10									Cr .8 Ni .4 V .4	Cr .8 Ni .4	Co .8
11										V .8 Fe .7	Mn .9 Fe .3
12											Ni .3
Total % data correlation accounted for	61.7	69	75.3	81	84.8	88.4		91.6	94.6	96.8	98.5

*Fe is equivalent to Fe_2O_3

Table 13: Minor element associations and loadings of R-mode factor models of drainage sediment data from Central Zambia (1159 samples)

result of the methods of matrix manipulation used and are not in themselves significant except where contrasting signs on the element loadings occur within the same factor association. Negative signs, therefore, have been neglected for the sake of simplicity, except where an element has significant loading value of opposed sign to the dominant elements in the association which would indicate a strong antipathetic relationship of that element with the others in the association. As has been discussed in section 4.5 methods have been suggested for selecting how many factors should be extracted. Ultimately, however, it is largely a subjective choice, based on the apparent meaningfulness of the associations of each factor model in terms of the possible features controlling the minor-element distribution, and the percentage of the intercorrelations that is explained by a particular model.

The 8 factor model which explains 88.4% of the intercorrelations was chosen as having the most explainable factor associations in terms of those expected from the initial interpretation of the regional distributions of single elements. The extent to which each association accounts for the intercorrelations is calculated by summing the squares of the factor loadings. This cannot, however, be done on correlated factors such as the Promax oblique factors. The associations of the orthogonal rotated varimax matrix are, however, similar to those of the Promax oblique matrix, only the difference between the high and low loadings on the elements have been increased by the Promax oblique rotation (Cameron, 1957). It was thought, therefore, reasonable to quote the sums of the squares of the loadings of the rotated matrix as a useful approximation of the amount of intercorrelation that each association from the oblique factor matrix explained. These values are entered into table 13 for the 8-factor model.

The minor-element associations extracted by the 8-factor model and their suggested explanations are as follows: (a) the Co-Ni-Cr association, explaining 16% of the intercorrelations, would reflect areas of basic rock; (b) the Mn-Fe_2O_3-V association, explaining 14% of the intercorrelations, would reflect the secondary environmental differences in rainfall and sample type; (c) the Pb-Ga associations, explaining 9% of the intercorrelations, would reflect granitic rock areas; (d) Sn, explaining 8% of the intercorrelations, would reflect the tin belt mineralisation; (e) Sr, explaining 8% of the intercorrelations, would reflect the carbonatite and to a lesser extent carbonate areas; (f) Zn, explaining 8% of the intercorrelations would reflect the Basement areas in general; (g) Cu-Ga association, explaining 7% of the intercorrelations, would reflect the copper metallogenic areas, and (h) the Ti-Cr-V-Ga-Fe_2O_3 association explaining 18% of the intercorrelations would reflect argillaceous rock units and their metamorphic derivatives such as shales and schists. This last association had not initially been recognised from the regional distribution of the elements; however, a similar association had been recognised in the data from the U.K. and the R-score patterns appeared to correlate with known areas of argillaceous rock (Khaleelee, 1969). Therefore, this association was tentatively considered to be reflecting similar lithologies in Zambia.

5.2.2 Significance of R-score variations in terms of minor element variations

The R-scores were calculated using the methods already described in section 4.5.5. In order to check the significance of the R-score variations in terms of minor-element variation and the analytical precision, the mean minor element value for all the elements were calculated for different classes of R-score value for each factor (Table 14). It was on the basis of these results that elements with loadings below 0.3 were not included in the factor associations. The minor element variations can be seen to decrease with the decrease in element loading and tend to be insignificant or of questionable significance in terms of the precision when the loading is below 0.3. There are exceptions to this arbitrary rule of thumb. For example, all the elements, with the exception of lead and strontium, in the Co-Ni-Cr association (Table 14a) increase in sympathy with the factor scores. These increases would be expected if the association were the result of basic rocks since most elements tend to be enhanced in basic rocks (Table 7). Other features, however, control these other elements more than basic rocks, and thus other associations are formed which reflect them. The fact that a minor element has a low loading in an association does not, therefore, necessarily indicate that none of its variation is accounted for by that association, but that most of its variation is explained by some other feature reflected by another association. This multiple control of element variation is sometimes reflected by mean element values which do not vary sympathetically with the R-scores. For example, Ga values in the Cu-Ga association are lower in the R-score classes greater than 1.0 than the R-score class between 1.0 and 0.5. It is only in the R-scores below 1.0 that Ga correlates with Cu. This characteristic would seem to indicate that there are at least two features controlling the Ga distribution of which one is reflected by its correlation within the 4-60 ppm range of Cu values, (Table 14(g)).

		R-score classes							
Element	Loading	>2.0	2.0–1.0	1.0–.5	.5–0	0–-.5	-.5–-1.0	-1.0–-2.0	<-2.0
Co	.8	100	60	55	45	33	24	18	8
Ni	.8	210	120	60	40	32	27	18	10
Cr	.4	110	100	100	80	60	34	28	12
Cu	.2	80	75	65	45	30	21	26	6
V	.2	170	190	230	120	81	64	60	40
Ti	.07	5000	5500	6600	5000	4000	4000	2800	1300
Fe_2O_3%	.07	9.0	8.0	9.2	4.6	3.8	2.9	2.7	1.3
Pb	.06	24	22	21	30	22	23	28	10
Sn	.002	4	4	4	4	4	5	5	4
Zn	-.002	120	130	110	100	70	60	50	50
Sr	-.02	90	130	120	90	90	90	100	150
Mn	-.02	460	460	580	410	310	290	180	10
Ga	-.07	35	25	30	26	21	15	20	7
No. of samples		11	20	23	25	24	23	24	14

N.B. all element values are in ppm except for Fe_2O_3 which is a percentage

Table 14(a): Co-Ni-Cr association

Table 14: Minor-element variations with R-score variation of the different factor associations

R-Score Classes

Element	Loading	>2	2.0	1.0	0.5	0	-0.5	-1.0	-2.0 <-2.0
Mn	.9	2700	1300	770	390	240	170	90	20
Fe_2O_3 %	.6	23	11	5.8	4.8	3.6	2.5	1.4	1.2
V	.3	300	180	110	100	90	90	50	32
Co	.2	60	60	37	35	34	29	26	22
Zn	.1	200	140	90	90	60	60	60	40
Ti	.1	8800	7000	5000	3900	4000	4000	3000	2000
Ga	.06	33	27	25	26	24	19	9	5
Sr	.01	160	120	130	100	100	100	90	90
Cu	.01	65	45	38	40	38	37	18	14
Pb	.01	32	29	18	34	25	25	17	12
Sn	-.004	6	5	4	5	5	5	5	4
Cr	-.06	80	70	65	55	60	65	50	30
Ni	-.1	50	45	35	35	40	40	35	32
No. of samples		15	25	21	22	23	23	22	17

Table 14(b): Mn-Fe_2O_3-V Association

R-Score Classes

Element	Loading	>1.0 1.0	0.5	0	-.5	-1.0	-2.0	<-2.0
Pb	1.0	70	50	30	22	11	5	1
Ga	.5	39	37	19	15	15	9	12
Mn	.1	520	480	330	290	320	250	200
Co	.07	28	39	35	33	33	30	33
Zn	.06	110	100	85	90	85	55	54
Ti	.04	4500	5000	3500	4000	4000	3500	4000
Sr	.03	90	100	100	100	110	100	100
Ni	.01	26	39	40	40	37	31	40
Sn	-.004	7	5	4	5	5	4	4
Cr	-.03	40	70	50	65	60	50	50
Cu	-.07	29	45	27	33	50	33	50
V	-.08	85	110	90	115	100	100	100
Fe_2O_3 %	-.09	4.4	4.0	3.8	4.3	4.2	3.5	3.9
No. of samples		22	23	23	23	19	22	24

Table 14(c): Pb-Ga Association

R-Score Classes

Element	Loading	>2	2.0	1.0	0.0 <0.0
Sn	1.0	22	9	5	4
Ga	.04	37	38	33	22
V	.03	140	155	120	94
Ni	.01	50	44	55	35
Zn	.01	90	100	80	110
Co	.01	40	40	45	37
Ti	.01	5500	5500	6500	4000
Mn	0	480	450	250	340
Sr	-.003	115	90	100	90
Pb	-.01	35	40	38	32
Cu	-.01	55	50	50	30
Fe_2O_3 %	-.02	5.2	5.2	4.6	3.4
Cr	-.04	65	80	80	75
No. of samples		33	12	35	15

Table 14(d): Sn Association

R-Score Classes

Element	Loading	>2	2.0	1.0	0.0 <0.0
Sr	1.0	550	200	100	90
V	.2	160	160	150	90
Pb	.04	40	27	18	34
Ni	.04	37	40	40	35
Fe_2O_3 %	.03	7.6	7.7	6.2	4.7
Cu	.02	30	60	34	40
Sn	-.002	4	4	4	4
Zn	-.01	140	110	70	100
Mn	-.02	830	540	280	450
Cr	-.03	60	70	70	60
Ga	-.04	25	26	22	26
Co	-.07	37	38	30	45
Ti	-.08	4000	4500	3000	4000
No. of samples		12	10	25	18

Table 14(e): Sr Association

R-score Classes

Element	Loading	>2	2.0	1.0	0.5	0.0	-0.5	-1.0 <-1.0
Zn	.9	350	220	130	95	50	45	40
Cr	.1	80	90	50	85	45	45	36
Fe_2O_3 %	.1	7.7	7.6	4.0	6.2	2.1	2.7	3.6
Pb	.06	39	32	14	20	24	16	22
Mn	.05	510	400	290	390	130	260	320
Cu	.04	50	50	33	55	20	23	27
Ni	.04	50	60	40	40	31	33	27
Sn	.01	5	5	6	5	5	4	6
V	-.002	140	150	85	110	60	80	35
Sr	-.01	110	90	90	90	110	110	90
Ga	-.04	29	23	22	34	9	13	27
Ti	-.05		5000	4000	5000	3000	3000	4500
Co	-.08	45	45	33	39	19	25	37
No. of samples		25	23	23	23	21	23	23

Table 14(f): Zn Association

R-Score Classes

Element	Loading	>2	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0 <-2.0
Cu	.8	260	130	60	43	32	21	10	4
Ga	.3	27	31	34	30	22	17	11	5
Co	.09	45	55	39	50	36	36	27	23
Ni	.06	65	60	45	45	40	35	25	23
Zn	.03	110	120	90	70	85	65	50	45
Fe_2O_3%	.03	7.8	6.8	5.7	4.7	4.2	2.3	2.4	1.5
Sr	.01	14	100	100	100	90	90	100	100
Mn	-.002	360	380	330	400	270	290	200	100
Sn	-.01	4	4	5	4	4	4	4	4
V	-.01	160	140	130	120	100	85	55	45
Ti	-.02	6000	5000	4000	4000	4500	4000	3000	2500
Cr	-.02	85	70	70	60	75	60	40	22
Pb	-.07	14	14	17	17	25	29	29	19
No. of samples		21	21	23	23	23	22	23	41

Table 14(g): Cu-Ga Association

R-Score Classes

Element	Loading	>2	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0 <-2.0
Ti	.8	9000	8000	7000	5000	4000	2500	1700	1300
Cr	.6	240	130	85	70	55	45	33	13
V	.6	390	290	150	100	85	70	50	31
Ga	.6	36	40	35	27	18	16	8	5
Fe_2O_3 %	.4	26.6	10.0	6.1	5.6	4.0	3.1	1.9	1.3
Ni	.2	55	70	55	39	36	32	27	16
Cu	.04	21	65	55	39	45	34	22	28
Mn	.02	1240	480	500	450	300	250	170	100
Zn	.002	300	90	100	95	85	60	50	50
Sn	.001	4	5	4	4	4	5	4	4
Co	-.003	50	50	45	38	37	30	24	21
Pb	-.01	21	10.0	22	27	25	17	17	15
Sr	-.02	190	90	100	90	100	90	100	90
No. of samples		4	23	23	22	23	24	23	21

Table 14(h): Ti-Cr-V-Ga-Fe_2O_3 Association

R-mode factor analysis will not necessarily pick out all the features controlling element variation, although it should indicate the main ones. Most of the other elements which have loadings of greater than 0.3 increase in sympathy with the R-scores through the whole range of R-score values, indicating: (a) the validity of choosing loadings of 0.3 and greater as a measure of the significance of an element in an association, and (b) the validity of the R-score contour intervals in terms of the variation of element value.

Tin and strontium show no values below -0.5 and zinc show no values below -1.0. This is due to the fact that the original element distributions are highly skewed because of truncation by their high detection limits, and because many of the samples are recorded as below the detection limit. Strictly speaking they should not have been included in the factor analysis, however, it will be shown later that their omission had no effect on the other associations (Table 17). Since they were thought to be single element associations from the initial appraisal of the data, they were retained for the sake of completeness.

The above discussion and tables have shown that R-scores of an association reflect a sympathetic variation of the elements which have loadings greater than 0.3 in that factor association. 0.3 appears to be a reasonable estimate of a significant factor loading because the element values with lower loadings do not correlate reliably with the R-scores.

5.2.3 Regional distribution of R-score variation of each association (factor) and their relation to casual features

The R-scores of each sample for each association have been plotted and the results contoured (Figs. 29-36). Since the values were plotted for each sample and no smoothing technique was employed before contouring, there is considerably more detail than is apparent in the moving-average maps. To some extent the inclusion of all the elements in the calculation of a sample value should have the effect of smoothing out some of the random components of the analytical and sampling errors, thus making the R-scores considerably easier to contour than the untreated minor element data. The contour intervals have been chosen on the basis of the results of the minor element variations with R-score value shown in Table 14 and on the basis of the extent to which each contour showed new features. That is to say if two contours intervals showed essentially the same patterns then one of them was not used for the sake of clarity.

(i) Co-Ni-Cr association

Cobalt and nickel are associated with the same high loading of 0.8; chromium has a lower loading of 0.4. High R-score values of the Co-Ni-Cr association occur over the areas of known basic rock outcrop (Fig. 29). There are extensive high R-score values over the Karroo Basalts around Livingstone, in scattered high areas in Lusaka East, just west of Lusaka, and in an area on the north side of the Lunsemfwa valley east of Broken Hill coincident with the Basement basic metavolcanics and hornblende schists. Extensive high areas occur to the north west of Lusaka in Lukanga south area, reflecting the basic rock units intrusive into the Katanga units there.

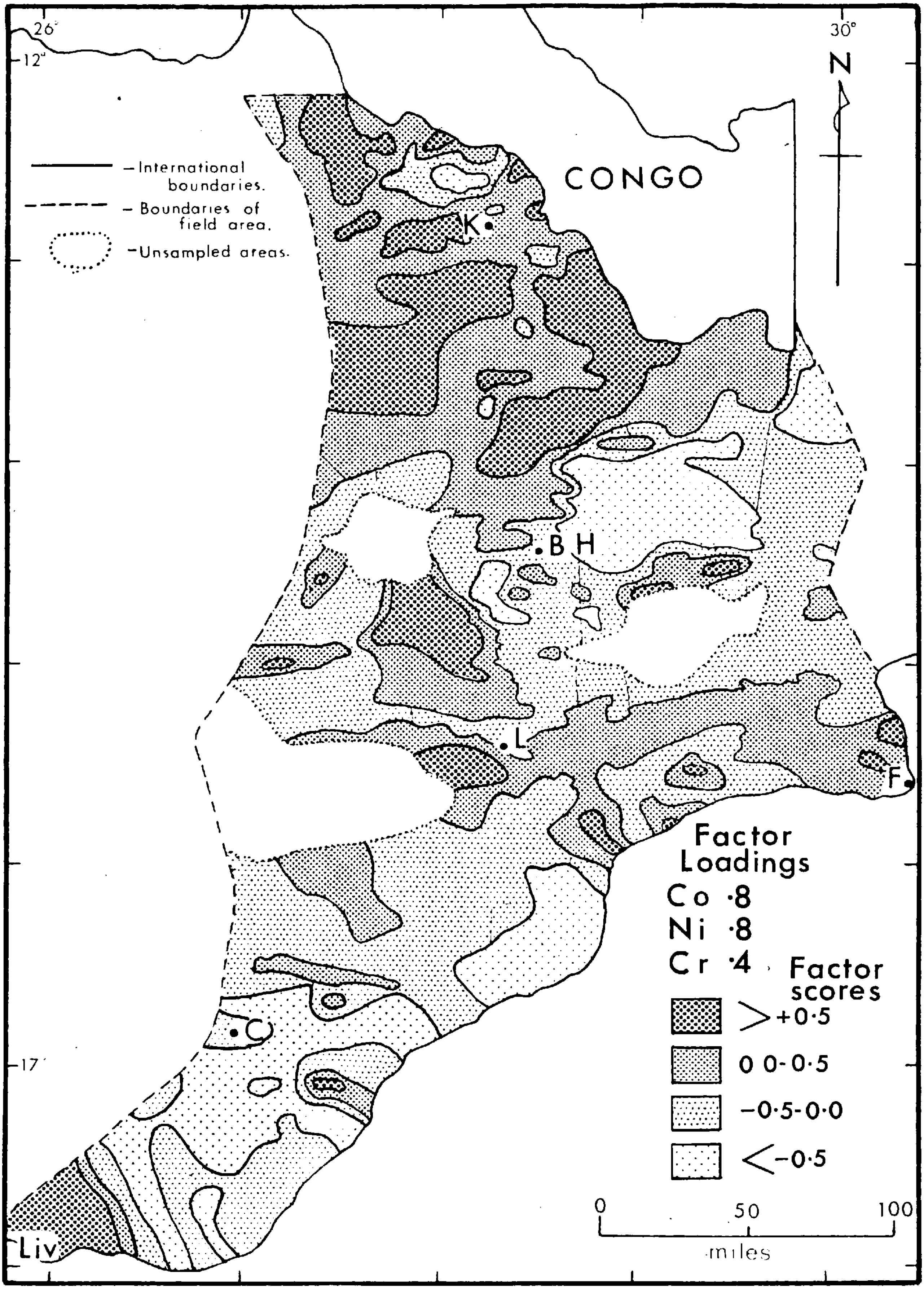

Fig: 29 Distribution of Co-Ni-Cr association R-scores.

There are also extensive high areas around the Copperbelt area in the north. Although basic rock units are known to occur in the northwest of the field area they have not been shown to occur as extensively as these patterns would indicate. It should be noted, however, that outcrop is very poor. In the Kadola area basic rock units, not previously mapped, were recognised by the factor associations from the geochemical drainage samples in that area, and confirmed by subsequent drilling, to be interbedded with Muva quartzite and schist units (see Chapter 6.2.3). These high Co-Ni-Cr association patterns would suggest, therefore, that basic rock units are probably a more common rock type in these areas than is suggested by present geological interpretations.

(ii) Mn-Fe_2O_3-V association

Manganese and iron are associated with loadings of 0.9 and 0.6 respectively with a somewhat lower loading for V of 0.3. A regional distribution of high R-scores (Fig. 30) shows a distinctive increase in the southern half of the field area following the moving-average patterns for the same elements but showing somewhat more detail. It is not known precisely what the smaller high R-score patterns are due to. They are thought to overly basic or carbonate rock outcrops. The overall increase in the R-scores of this association to the south, however, is undoubtedly a reflection of the secondary environmental features already discussed in the previous section (5.1.5).

(iii) Pb-Ga association

This grouping is a lead, gallium association with loadings of 1.0 and .5 respectively. Samples with high R-scores in this factor occur in the east and south of the field area and the patterns correspond

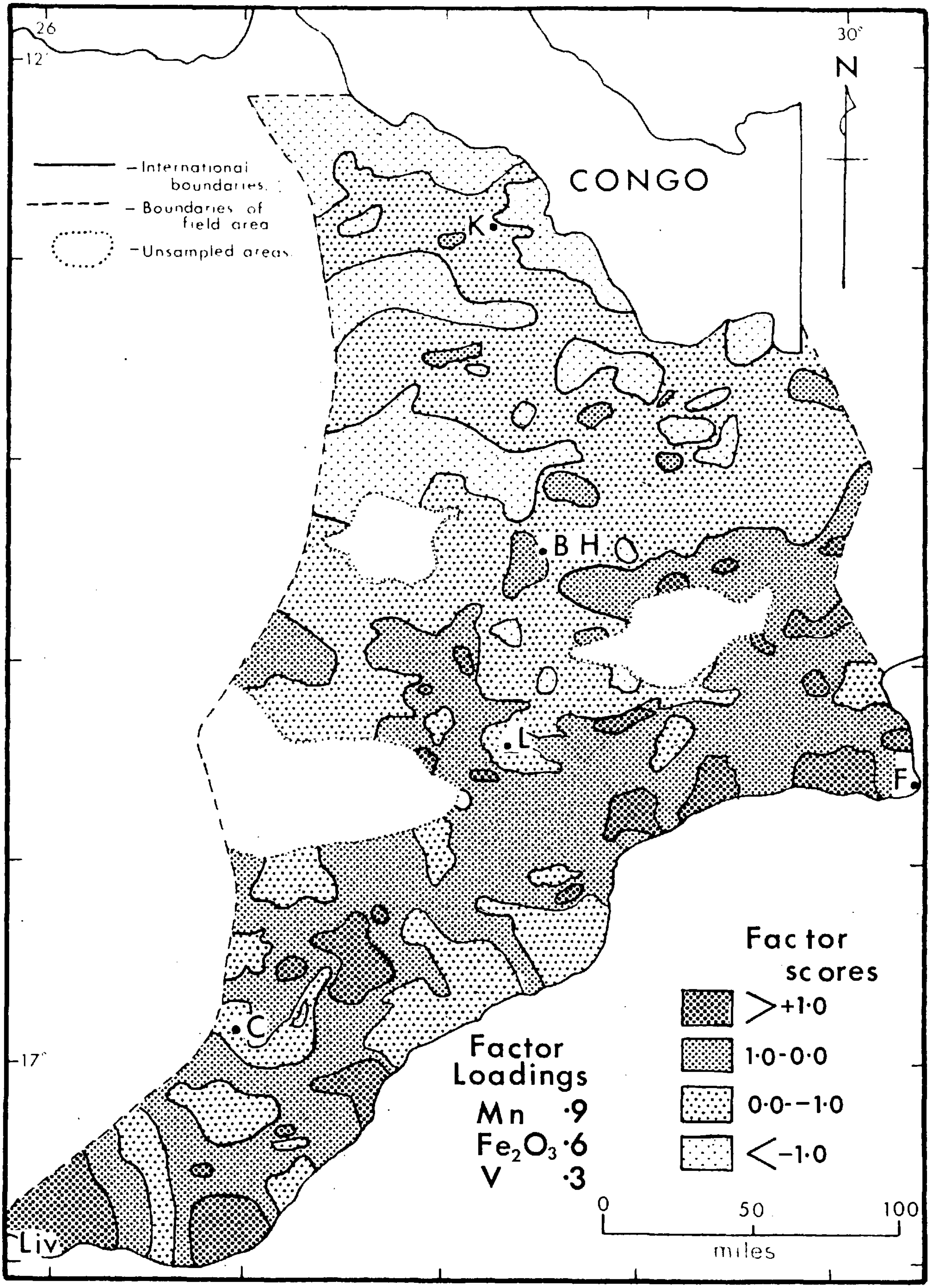

Fig: 30 Distribution of Mn-Fe_2O_3-V association R-scores.

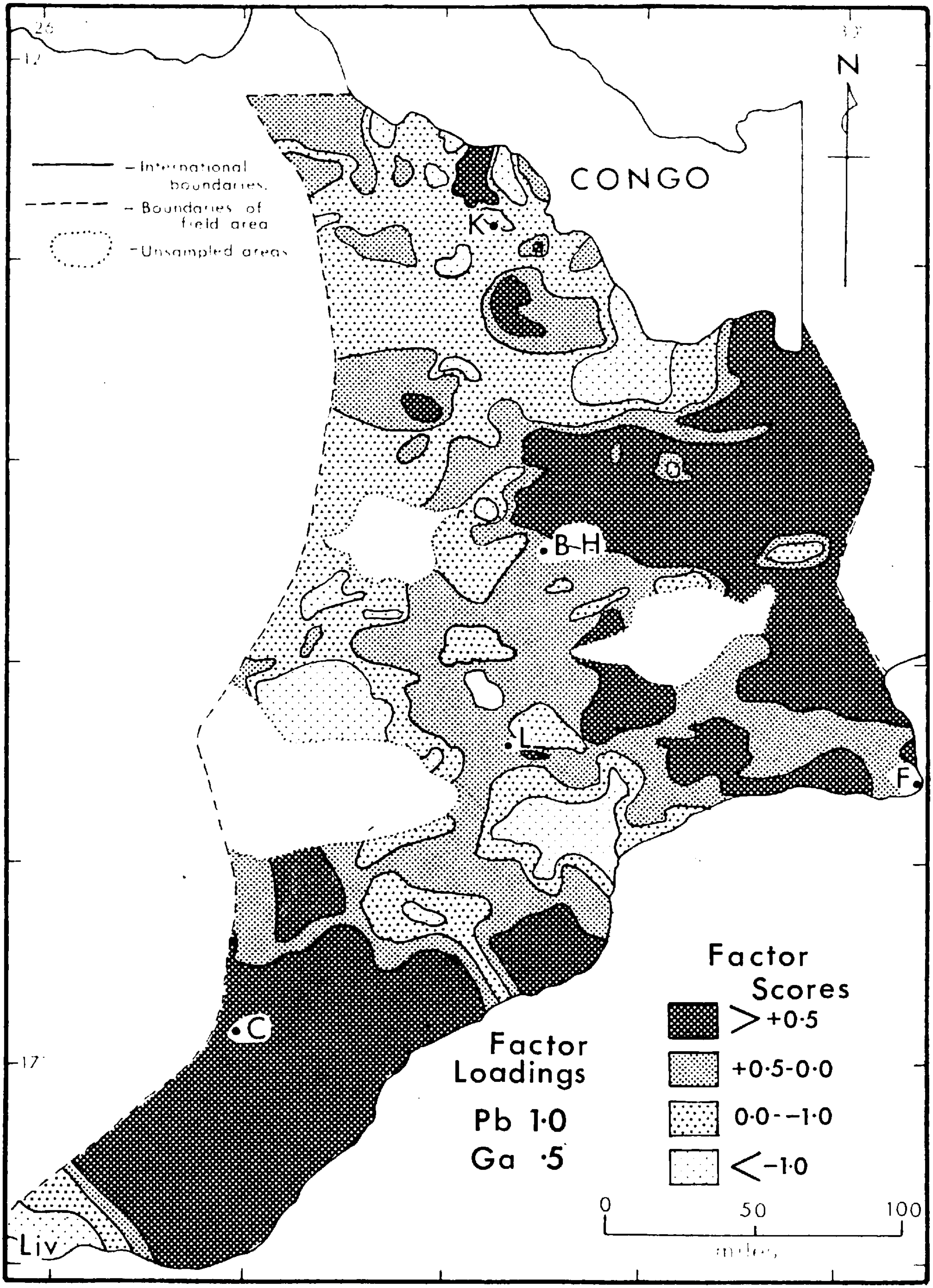

Fig: 31 Distribution of Pb-Ga association R-scores.

well to the outcropping of granite and granite gneiss (Fig. 31).

(iv) Sn association

A single element association with a loading of 1.0 on tin is extracted. As had already been noted, the reason that tin stands out so strongly as an individual factor is probably due to some extent to non-normality of its frequency distribution because most of the samples are below detection limit. The resultant Sn R-score patterns are identical to the untreated data plots (Fig. 32). The most significant high pattern centres around the Choma tin belt, which corresponds well with the high moving-average patterns. There are scattered patterns elsewhere but except for a pattern in the Lukanga south area they are not extensive.

(v) Sr association

A single element association with a loading of 1.0 on strontium is extracted. As with tin, the non-normal frequency distribution of strontium resulting from the large number of samples below the detection limit, has probably given rise to strontium being extracted in a factor on its own. The resultant Sr R-score patterns are similar to the untreated data with the main patterns occurring in the extreme west in association with carbonatites, and in the extreme south west in association with the Karroo basaltic lava flows. There is, in addition, however, a north west to south east trending belt east of Mazabuka which parallels the structural trend of underlying carbonate rocks (Fig. 33). There are also a few scattered high strontium patterns associated with carbonate rocks elsewhere.

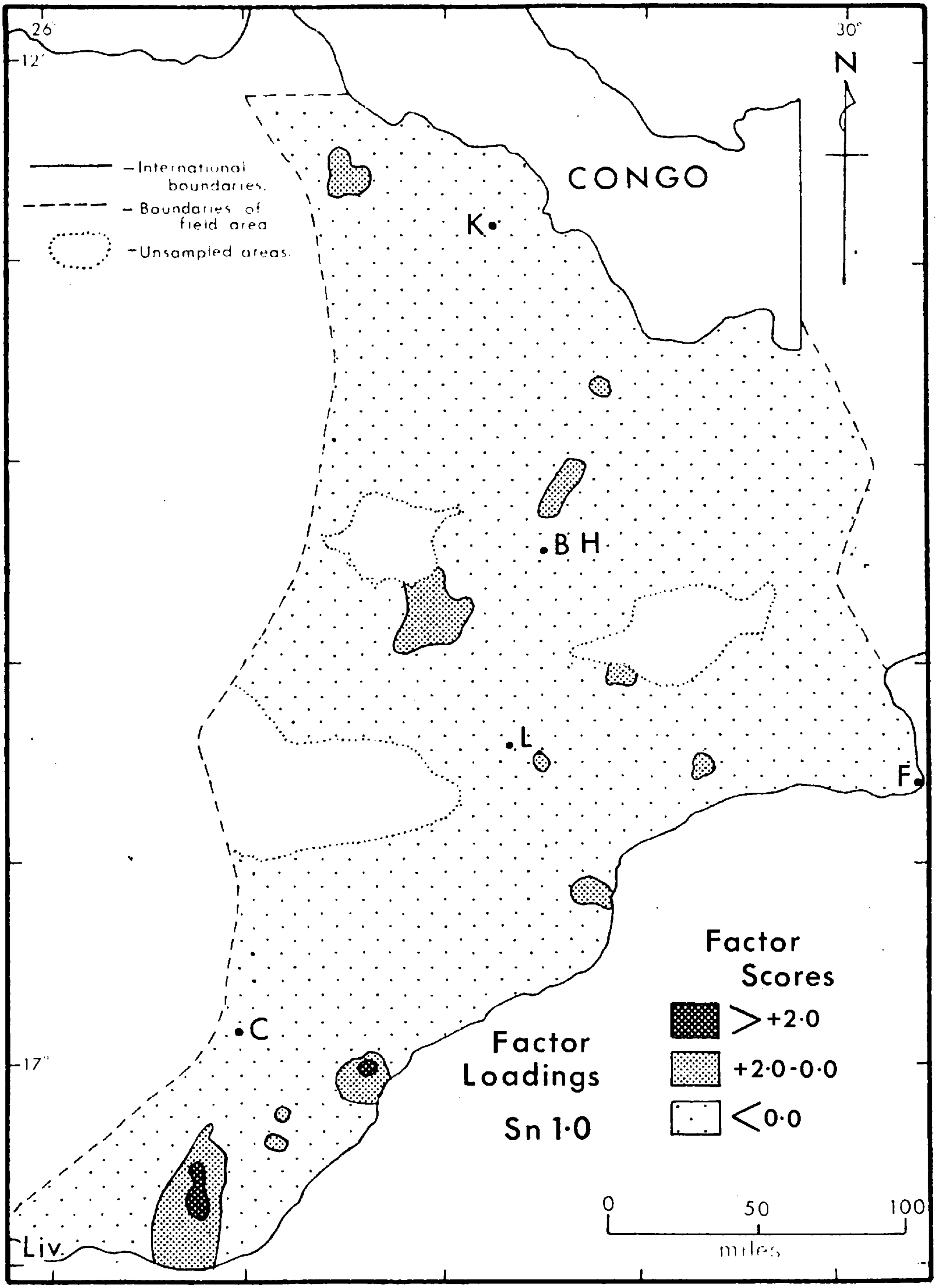

Fig: 32 Distribution of Sn association R-scores.

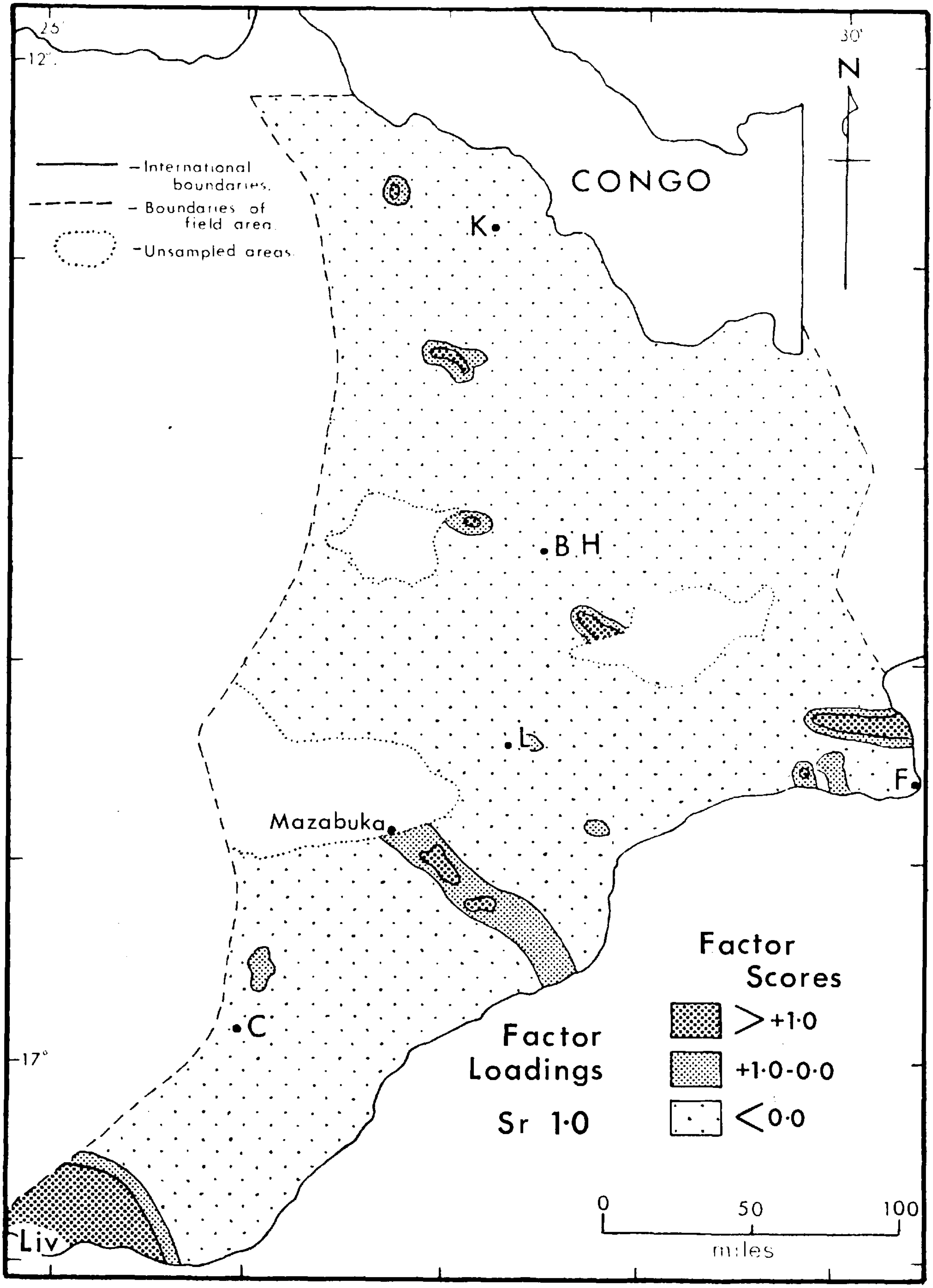

Fig: 33 Distribution of Sr association R-scores.

(vi) Zn association

A single element association with a loading of 0.9 on zinc is extracted. Zinc suffers from the same disabilities as tin and strontium factors although to a lesser extent. Thirty per cent of the samples are below the zinc detection limit. The resultant factor scores are noisy and difficult to contour, but in general there are higher scores to the east and south over the Basement Complex, basic rocks and Karroo basalts, and low scores over the Katangan units (Fig. 34).

(vii) Cu-Ga association

A Cu-Ga association is extracted with a strong loading of 0.8 for copper and a weak loading of 0.3 for gallium. The patterns of high Cu-Ga association R-scores are similar to the copper moving-average map except that there is more detail and some of the large moving-average patterns are divided into smaller areas (Fig. 35). The strongest pattern centres on the Copperbelt area where factor R-scores are mostly greater than 1.0 with scattered samples greater than 2.0. This area coincides with the main copper metallogenic province of the Copperbelt. It is important to note that the Cu-Ga high R-score patterns in the Copperbelt are not exactly coincident with high Co-Ni-Cr high R-score patterns. This demonstrates that the high Cu values in the Copperbelt are not due to basic rocks. A similar conclusion can be postulated for the belt of high Cu-Ga association R-scores running east and west of Lusaka, where there are also high Co-Ni-Cr association R-scores. The correspondence, however, between the patterns of the two associations is not exact which suggests that the Cu-Ga association is a possible reflection of the copper metallo-

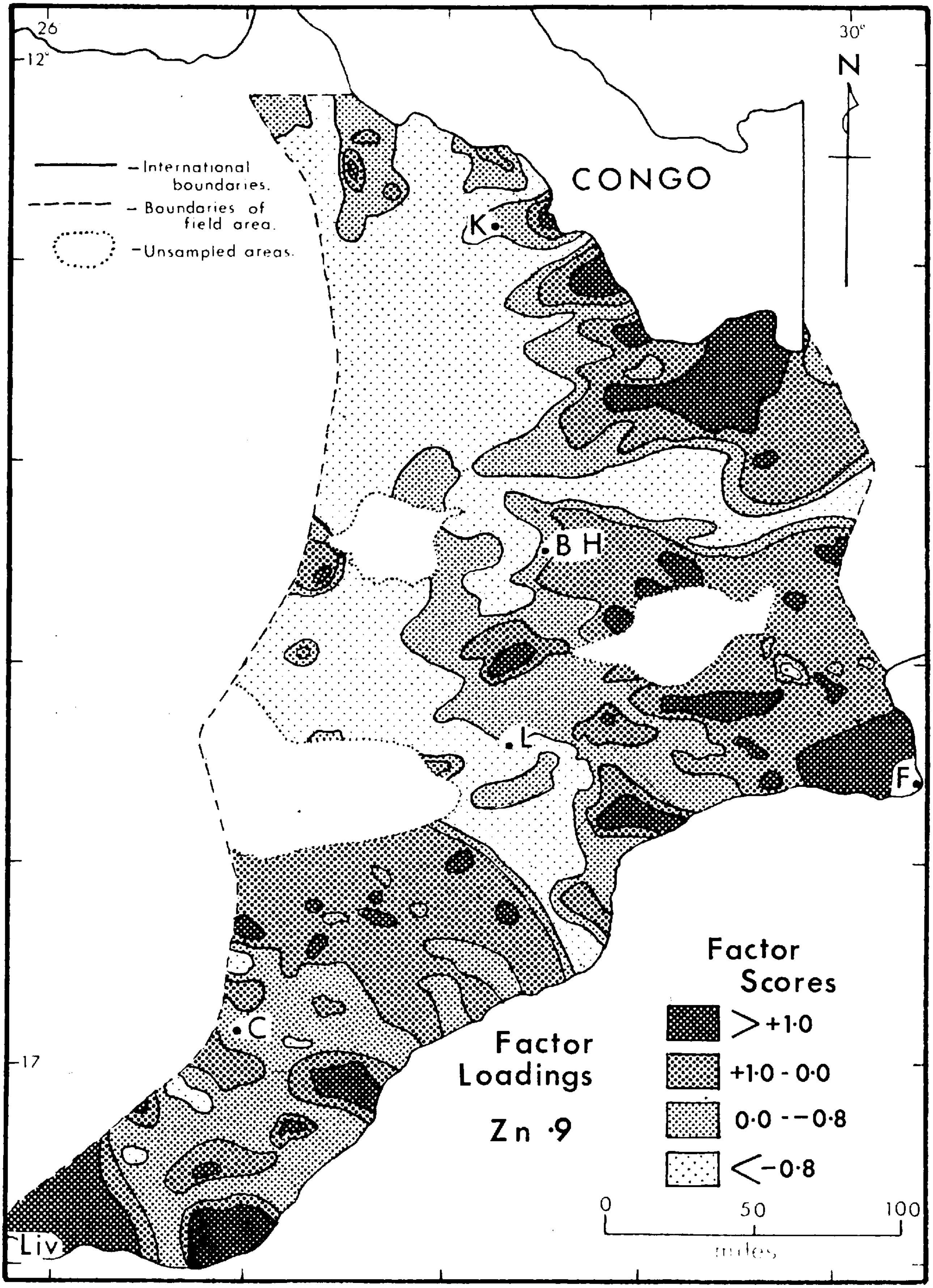

Fig: 34 Distribution of Zn association R-scores.

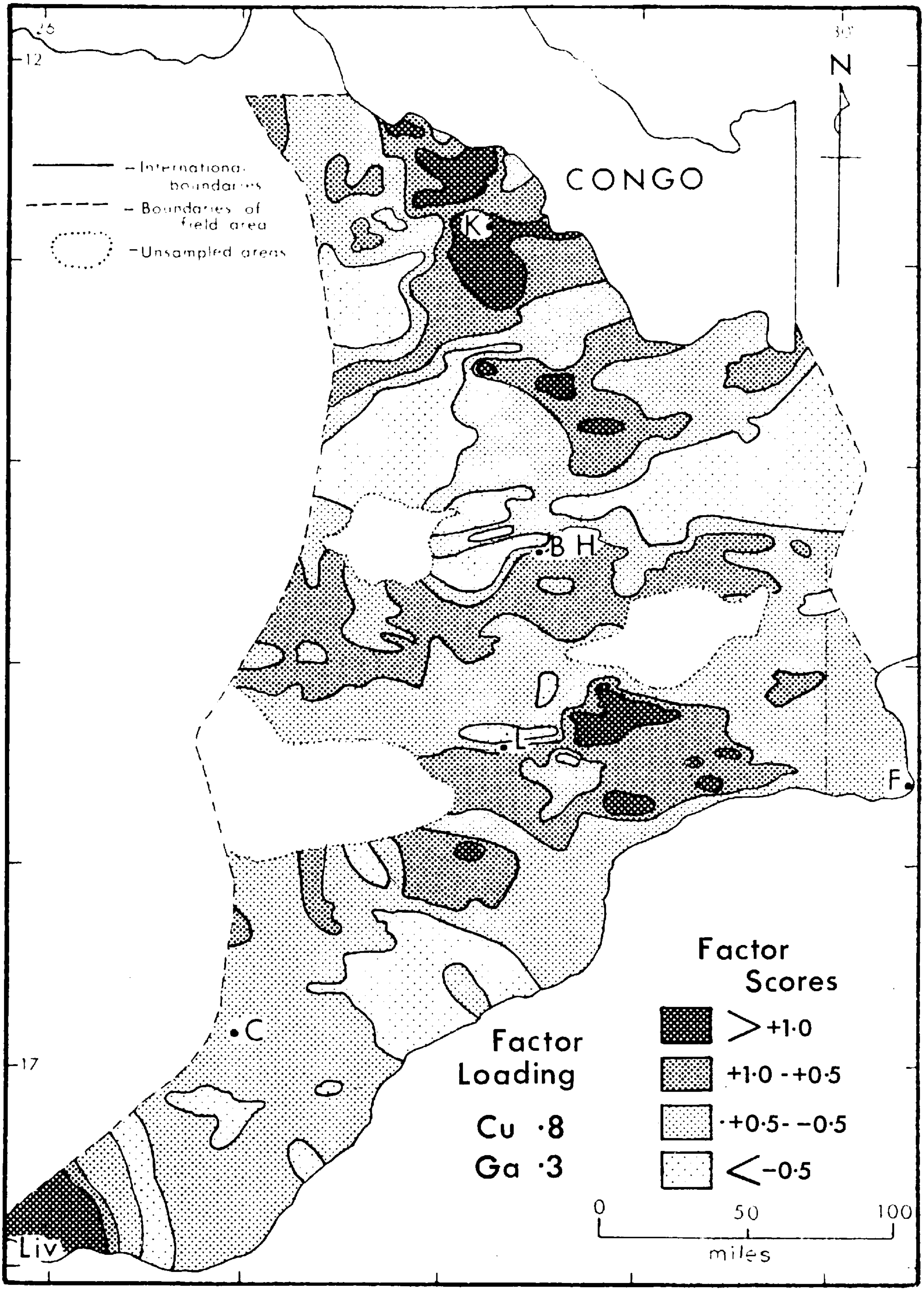

Fig: 35 Distribution of Cu-Ga association R-scores.

genic district in that area as well as the prevalent basic rock units. An east to west trending belt of Cu-Ga R-scores in the 1.0 to 0.5 range occurs just south of Broken Hill and Lukanga Swamp and north of the Lunsemfwa valley. This belt of higher copper values was not defined by the copper moving-average analysis because of the degree of smoothing. The eastern end of the belt north of Lunsemfwa valley corresponds to a pattern of high Co-Ni-Cr R-scores where basic rocks are known to occur. Similarly, the western end of the belt south of Lukangan Swamp corresponds to high Co-Ni-Cr R-scores where basic rocks probably occur. This leaves only the central portion of the belt immediately south of Broken Hill possibly indicating a copper metallogenic belt. The lower R-scores (copper values) in this area compared with those in the Copperbelt and Lusaka areas, however, would not make it a prime exploration target. The high Cu-Ga association R-scores in the south west around Livingstone are due to the Karroo basalts in that area.

(viii) Ti-Cr-V-Ga-Fe_2O_3 association

A general association of Ti, Cr, V, Ga and Fe_2O_3 with loadings of 0.8, 0.6, 0.6, 0.6 and 0.4 respectively, is extracted. Patterns of samples with high Ti-Cr-V-Ga-Fe_2O_3 R-scores occur in relatively well defined areas throughout the field area, often paralleling structural trends and coinciding with areas of extensive schist belts of the Basement or argillaceous units of the Katangan system (Fig. 36).

5.2.4 Discussion of factor analysis results

The single element factors, Sn, Sr and Zn and the Cu-Ga, and Mn-Fe_2O_3-V associations have essentially confirmed the distributions

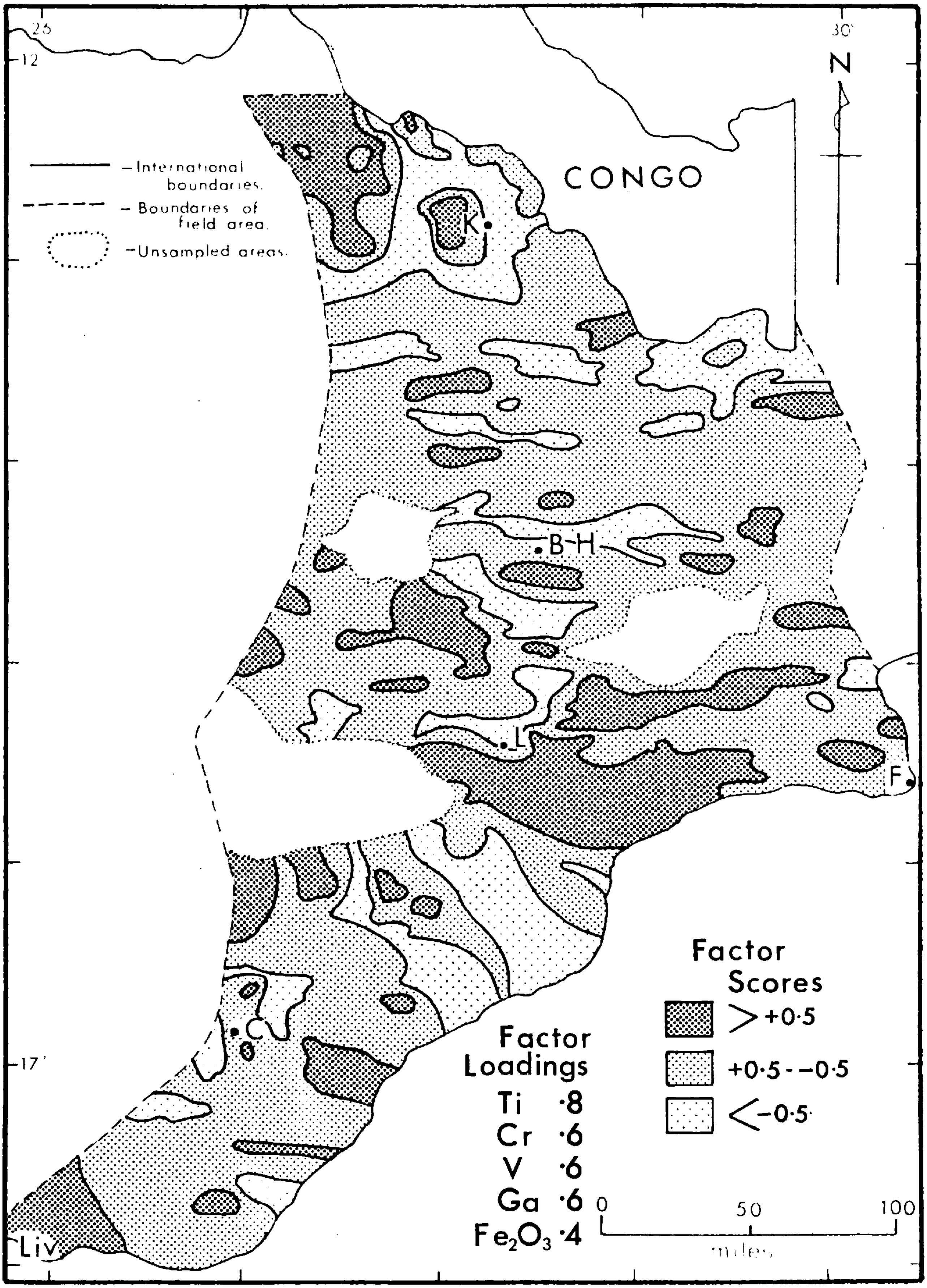

Fig: 36 Distribution of Ti-Cr-V-Ga-Fe_2O_3 association R-scores.

of the main elements in these associations, defined by the moving-average analysis. The only difference has been in the greater detail due to contouring around single sample points. The geochemical association of gallium with copper and vanadium with manganese and ferric iron was previously unsuspected.

Gallium is normally associated with aluminous rich clays and therefore argillaceous rocks, shales and schists (Rankama and Sahama, 1949). Copper mineralisation is associated largely with argillaceous rocks in the Copperbelt (Mendlesohn, 1961) and biotite schists in the Lusaka East and Lusaka area (Pienaar, pers. comm.). It seems possible, therefore, that the Cu-Ga association may be due to the common source rocks for these two elements. It is also possible that the Cu-Ga association is reflecting a secondary environmental affinity. Assuming the gallium content in the dambo sediments to be controlled by clays, because of its substitution for aluminium, and the copper content by absorption by these same clays, it would seem reasonable to suggest some Cu-Ga correlation. Although this possibly explains the association of copper with gallium, it is not likely to explain the variation of copper in the plateau areas, (a) because of the relatively uniform drainage sediment types, (b) because the correlation of Cu-Ga has been shown to occur only when copper values are below 60 ppm. In other words, copper values are independent of gallium values in certain circumstances, and in particular when copper values are greater than 60 ppm (Table 14g), and (c) because the Cu-Ga R-scores will be controlled mostly by the copper content because of its dominant loading of 0.8 compared to gallium's loading of only 0.3.

The reason for the association of vanadium with manganese and ferric oxide is also not clear. Vanadium is known to substitute for iron in iron rich minerals in igneous basic rocks and clays and shales (Rankama and Sahama, 1949). Since vanadium does not have the same clear enhancement in the southern half of the field area (Fig. 21) as manganese or ferric oxide, its inclusion with the Mn-Fe_2O_3 association seems to be a reflection of its general affinity for iron rather than a similar method of redistribution in the secondary environment as manganese and iron.

The Co-Ni-Cr factor is an expected association of elements derived from basic rocks. Their combination into a single parameter has made it possible to interpret the contour patterns of these three elements more easily, and it is hoped that the Co-Ni-Cr R-scores indicate the true disposition of the basic rocks.

The Ti-Cr-V-Ga-Fe_2O_3 factor was not an expected association from an interpretation of the original data. They are all elements, however, known to be higher in argillaceous rocks (op. cit.). This fact coupled with the similar factor being extracted, which appeared to reflect argillaceous units,from the U.K. data (Khaleelee, 1969), suggested that R-score patterns of this association would show high values over argillaceous or schistose units. The combination of these elements has made it possible to identify a feature controlling their distribution, and the R-scores patterns are more meaningful in terms of the geology than the single element patterns. It should be noted, however, that most of the elements in this association are also high in basic units. R-scores of this association, will therefore also tend to be high over basic as well as schistose rocks.

5.3 COMPARISON OF MINOR ELEMENT CONTENT AND FACTOR ASSOCIATIONS EXTRACTED FROM BEDROCK AND SOIL SAMPLE DATA TO THOSE FROM DRAINAGE SEDIMENT SAMPLE DATA

5.3.0 Introduction

In the previous sections, minor-element and factor associations and their R-score patterns extracted from drainage sediment sample data have been interpreted using available geology, soil and rainfall maps and a background knowledge of mineralisation within the field area. In order to establish more definitely the causes of the minor-element variations and their associations in the drainage sediment, rock, soil and further drainage sediment samples have been taken along road traverses which cross the main minor element and R-score patterns.

The main route selected for this sampling traverse was along the main road running from the Copperbelt high copper area in the north, to the Choma tin high area in the south (Fig. 37). A traverse to the east of Lusaka along the Great East Road was made in order to cross the zinc patterns associated with the Basement rocks to the east. Significant highs and lows of other element patterns were also crossed by these routes. The soil and rock samples were taken at a closer interval along the traverse routes than the drainage samples since they were thought to be considerably less representative of the sampled area as a whole since: (a) a drainage sample tends to be a composite sample of upstream source material, and (b) the traverses were linear rather than areally distributed.

The rock and soil samples were prepared and analysed as described in sections 4.3 and 4.4.

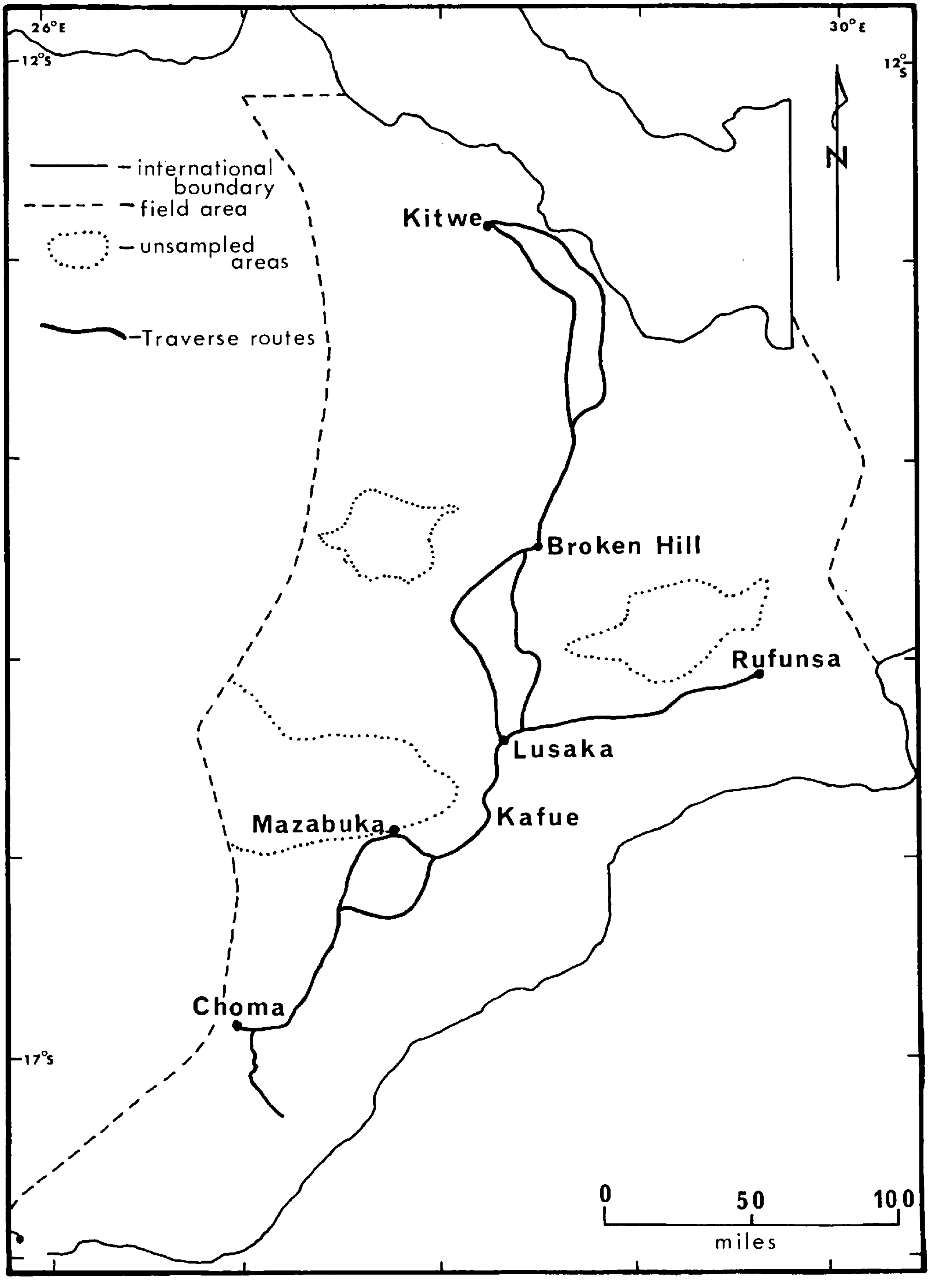

Fig: 37 Location of traverse route of rock, soil and replicate drainage sampling.

5.3.1 Minor element values of rocks in metallogenic provinces and districts

Patterns of high copper background from drainage sediment samples appear to have defined the copper metallogenic province of the Copperbelt and the copper district in the Lusaka area, and a high tin background pattern appears to have defined the Choma tin belt. In order to show that these enhanced copper and tin values are reflecting an increased background in the rocks in general, the mean element values of rock types in these areas have been compared with those from similar rock types elsewhere.

The mean and standard deviation range of Co, Cu, Cr, Ni, Pb and Ti of different lithologic and stratigraphic units in different parts of the field area are shown in Table 15(a). (The area names used in this table refer to those already defined in Fig. 26.) These results show copper to be highest in all the Basement units in the Copperbelt area compared to the same units elsewhere. Mean copper values in the Basement siliceous schists in the Copperbelt are 3-4 times the same lithologies elsewhere. The Basement schists and granite gneisses in the Copperbelt have greater copper contents than the same rock types elsewhere. The high Co, Cr and Ni mean values of these rock types. in the Copperbelt compared to elsewhere, suggest, however, that mafic minerals could be responsible for the enhanced copper values. In addition, the number of samples and the difference in values are not large enough to give statistically significant differences. The Kolmogorou-Smirnov statistic (Table 15(b)) shows that the copper values of the Basement siliceous schists from the Copperbelt are statistically significantly higher than the Lusaka East siliceous schists and Kadola siliceous schists at the 99% and 80% respectively

Lithologic & Stratigraphic Units		Basement Siliceous Schists				Basement Schists					Basement Granites and Gneiss					Katangan Schists (Mwashia and Kundelunga)			
Element	Area	Copperbelt	Lusaka East	Lukanga South	Kadola	Copperbelt	Lusaka East	Lukanga South	Kadola	Kafue to Choma	Copperbelt	Lukanga South	Kadola	Broken Hill	Kafue to Choma	Copperbelt	Lukanga South	Kadola	Kafue to Choma
Co	Mean*	24	17	14	19	32	26	21	19	21	23	19	16	25	15	15	31	20	26
	Range**	14-45	9-30	10-21	13-28	21-50	13-50	14-33	12-32	12-38	13-40	13-27	10-26	17-37	11-21		18-50	11-34	18-37
Cr		65	55	60	80	140	70	45	100	75	70	45	55	45	45	60	85	90	70
		33-120	31-100	33-100	38-160	95-210	26-390	37-50	50-190	48-120	29-160	34-55	28-100	31-60	34-55		45-150	40-185	40-130
Cu		45	10	15	16	26	18	12	25	20	27	16	21	23	11	28	28	28	19
		14-130	7-17	10-22	7-37	13-50	5-150	9-17	8-70	8-50	12-60	8-30	7-67	14-38	5-23		10-80	11-70	7-50
Ni		29	17	21	18	32	26	21	19	21	33	20	28	18	19	36	40	26	35
		18-45	9-30	14-30	12-29	21-50	14-50	14-33	12-32	12-38	17-65	11-36	13-60	11-28	11-33		20-90	15-45	20-55
Pb		4	4	4	5	4	5	5	6	12	5	11	5	12	14	4	4	4	4
									3-11	5-26	3-6	5-22	3-8	5-27	7-28				
Ti		6000	7200	7100	6700	9100	11,612	6500	7000	7300	5500	3300	3200	3500	2100	5300	10,900	6200	7500
		3900-9200	5200-10,000	3200-16,000	2600-17,000	5900-14,200	6200-21,900	4070-10,300	2200-22,000	3400-15,600	3800-8000	1500-7200	1500-7100	1100-11,100	700-6300		6300-19,000	3200-12,000	4500-20,000
Zn		27	19	13	22	23	45	25	18	55	24	26	40	35	35	25	40	25	26
		9-80	8-45	9-18	8-60	11-45	13-150	10-60	10-30	22-140	11-50	11-60	22-75	13-90	16-70	5-130	14-110	10-60	10-65
No. of samples		6	15	16	8	6	12	7	10	15	16	17	19	15	16	6	17	7	24

*Geometric mean

**Single standard deviation range

Table 15(a): Mean and standard deviation ranges of minor elements in same lithology and stratigraphic units in different areas.

	Lusaka East	Lukanga South	Kadola
Copperbelt	99%	N.S.*	80-90%
Lusaka East		N.S.	80-90%
Lukanga South			N.S.

*N.S. - not significant or below 80% probability difference

Table 15(b): Statistical significance according to the Kolmogorov-Smirnov test in % probability level of the different copper values in Basement siliceous schist rock samples from different areas.

	Lusaka East	Lukanga South	Kadola	Broken Hill	Kafue to Choma
Copperbelt	95-98%	N.S.*	N.S.	N.S.	90-95%
Lusaka East		N.S.	N.S.	95-98%	N.S.
Lukanga South			N.S.	90-95%	N.S.
Kadola				N.S.	N.S.
Broken Hill					99%

*N.S. - not significant or below 80% probability difference

Table 15(c): Statistical significance according to the Kolmogorov-Smirnov test in % probability of the different copper values in Basement granites and gneiss rock samples from different areas.

but is not significantly different from the Lukanga South values. The same test on the copper values of the Copperbelt compared to all the other siliceous schist values showed that they were significantly higher at the 98% probability. The same test on the copper results from Basement granites and gneisses show that those from the Copperbelt are significantly higher than the Lusaka East, and Kafue to Choma results at the 95% and 90% probability level respectively (Table 15(c)). The Copperbelt copper values are not significantly different from the Broken Hill copper values. The Broken Hill copper values in the Basement granites and gneisses have surprisingly high copper values considering the relatively low copper values in the drainage sediment in that area.

The only Katangan units which could be sampled in the Copperbelt were the Upper Katangan Mwashia and Kundelunga schistose units, and these were not fresh specimens but weathered and had a leached appearance. No particular enhancement of mean copper value was noted from these rock types.

Enhanced mean copper levels were not detected in rocks from the Lusaka or Lusaka East areas in any of the rock types.

The soil data gives considerably less ambiguous results than the rock data. Soil samples from the Copperbelt have an almost twofold increase in mean copper level compared to soil samples from elsewhere (Table 16(a)). The Kolmogorov-Smirnov statistic shows that this value is statistically significantly higher than all the other values at the 99% probability level (Table 16(b)). In addition, there is no sympathetic increase in Co, Cr or Ni values in the Copperbelt soils compared to elsewhere indicating that basic rocks are not the

Area Element	Copperbelt	Broken Hill	Kadola	Lusaka East	Kafue to Choma
Co	20 12-35	24 16-35	20 13-30	25 16-40	17 11-26
Cr	60 40-90	60 40-100	60 35-100	100 40-220	70 40-110
Cu	30 15-60	16 9-28	18 9-35	20 8-55	17 8-35
Mn	75 45-120	130 55-290	110 50-230	150 70-350	160 70-390
Ni	22 11-40	17 10-29	19 11-33	23 11-50	16 9-27
Pb	7 3-13	12 4-35	7 3-15	6 3-13	16 8-35
Ti	17,000 13,000-22,000	18,000 14,000-24,000	18,000 13,000-24,000	20,000 16,000-24,000	17,000 12,000-23,000
Zn	22 13-35	30 14-65	20 12-35	19 11-50	30 18-50
No. of samples	40	53	58	64	98

Table 16(a): Mean content and single standard deviation ranges of minor elements in soil samples in different areas.

	Lusaka East	Kadola	Broken Hill	Kafue to Choma
Copperbelt	99%	99%	99%	99%
Lusaka East		NS	NS	80-90%
Kadola			NS	NS
Broken Hill				NS

Table 16(b): Statistical significance according to the Kolmogorov-Smirnov test in % probability levels of the different copper values in soil samples from different areas.

explanation for the enhanced copper values. Mean copper values in the soils from Lusaka East are consistently higher than the other areas, with the exception of the Copperbelt, although it is only statistically significantly higher at the 80% probability level from mean copper value of the Kafue to Choma soil samples.

In conclusion, therefore, the general higher copper values in the Copperbelt Basement rocks, and in the Copperbelt soils, substantiates to some extent the hypothesis that the enhanced copper values in the drainage data is due to a background increase of copper in the rocks. The lack of an adequate number of rock samples, and the inability to be sure of representative fresh rock samples, because of poor outcrop, makes it impossible to verify the hypothesis with certainty. The limitations of gaining information of the primary regional geochemistry from rock sampling compared with drainage sediment sampling is, however, shown in this example.

There is little if any evidence that there is an increased copper background in the rocks of Lusaka East metallogenic district. The enhanced copper background of the drainage sediments in the Lusaka East area is, therefore, most probably the result of a greater frequency of minor copper mineralisation suggested earlier. Even if this is the explanation for the increased regional copper values in the drainage sediment in both the Copperbelt and Lusaka East, it does not detract from the usefulness of wide interval drainage sediment sampling as an exploration method for defining metallogenic districts or provinces.

In the Choma tin belt, outcrop is good and relatively fresh rock samples were collected. Detectable levels of tin (greater than or equal to 5 ppm) occurred in 15 (94%) out of 16 Basement rock samples from the area, of which 5 samples (30%) are above the 5 ppm detection limit compared to similar lithologies elsewhere which have detectable tin in only 8 out of 14 samples (50%) of which only 3 (16%) have values above 5 ppm.

The Kolmogorov-Smirnov statistic indicates that these increased tin values of rocks in the Choma tin belt are statistically significant at the 99% probability level. It is also significant from the point of view of the genesis of the tin and rock sampling in order to detect tin metallogenic districts, to point out that the highest tin values of 40 ppm occurred in the schists and not in the granitic rocks in the area. It had been assumed in the past that the tin bearing pegmatites were probably related to the Choma granite batholith (Drysdall,1967). Recent workers in the Geological Survey of Zambia have suggested, however, that these tin bearing pegmatites are associated with an earlier granite which has since been converted to a phyllonitic schist by metamorphism and tectonic movement (G. Matheson, pers. comm.). Therefore, if only granite rocks had been sampled in the area in order to detect a tin bearing province, as has been suggested in the past (Goloubinoff,1937),and if insufficient geologic work had been done to recognise the phyllonitic schists, the tin bearing districts of the Choma tin would not be detected. This is yet another argument for the use of general drainage sediment sampling rather than rock sampling as a means of detecting regional primary geochemical differences related to metallogenic districts.

In addition, there is a similar though higher proporation of soil samples, than drainage or rock samples, from the Choma tin belt with detectable tin values. Out of 18 soil samples within the Choma tin belt area, 8 samples (42%) have tin values greater than the 5 ppm detection limit, 6 samples (32%) have values of 5 ppm and the remaining 5 samples (26%) are below 5 ppm. Outside the Choma area over similar lithologies, only 1 sample out of 28 (3%) had tin values over 5 ppm, 5 samples (9%) have tin values of 5 ppm and 24 samples (86%) have values below 5 ppm. This increased incidence of tin in the soils of the Choma tin belt is statistically significant at the 99% probability level according to the Kolmogorov-Smirnov test. This confirms the general findings from the drainage and rock data. In addition, the increased proportion of tin in the soils compared to the drainage and rock data, suggests concentration of the tin-bearing minerals in the residual soil which agrees with Schiefler's (1967) findings. If this is the case, then broad interval sampling for tin metallogenic districts could just as easily be done by soil as drainage sampling in areas of residual soils.

In conclusion, therefore, the high tin background values found in the drainage sediment in the Choma tin belt definitely reflect a general increase in tin content of the rocks in that area. In addition, analysis of wide interval drainage sediment samples should be an adequate method for detecting and defining tin metallogenic districts or provinces.

5.3.2 Comparison of R-mode factor associations extracted from the minor element data of rocks, soils and drainage sediment samples

The variations in minor-element background and the factor association R-scores of the drainage sediment data have been related to various primary and secondary features on the basis of the correspondence of their regional patterns with the incidence of particular features. Assuming these interpretations to be correct, it should be possible to extract essentially the same factor associations and define similar minor element regional patterns from the rock and soil data. Since the single element moving average regional distributions gave little additional information than R-score patterns, only the factor analytical solutions of the data from the different types of sample have been compared.

As has already been stated in section 4, due to various analytical contingencies, tin, strontium and ferric oxide could not be analysed on all the samples taken during the second field season; therefore, only ten elements including Co, Cr, Cu, Ga, Mn, Ni, Pb, Ti, V and Zn were used in the factor analysis computation of samples. In order to be able to compare the factor associations from the initial drainage sample data with those from the subsequent follow-up data, the initial data was factored omitting the Fe_2O_3, Sn and Sr analyses. The results of the six factor model omitting these elements are compared with the original eight factor model (Table 17). The associations of the two factor analytical solutions are identical with the omission of the Sn and Sr factors and Fe_2O_3 from the Mn and Ti associations. The order of the factors has been changed a little but the percentage of data correlation of the two factor solutions are of similar magnitude.

Factor	Original Sampling				Replicate Sampling %	
	All data	%*	Fe_2O_3, Sn & Sr omitted	%*		%
1	Co 0.8 Ni 0.8 Cr 0.4	16	Ni 0.9 Co 0.8 Cr 0.5	22	Cu 0.9 Co 0.6 Ni 0.4	16
2	Mn 0.9 Fe_2O_3 0.6 V 0.3	14	Zn 1.0	10	Pb 1.0 Ga 0.6	14
3	Pb 1.0 Ga 0.5	9	Pb 1.0 Ga 0.4	12	Ti 0.9 Cr 0.6 V 0.5 Ga 0.3	17
4	Sn 1.0	8	Ti 0.8 Ga 0.6 V 0.6 Cr 0.5	21	Mn 0.9 V 0.6	14
5	Sr 1.0	8	Cu 0.8 Ga 0.4	10	Ni 0.9 Cr 0.4	11
6	Zn 0.9	8	Mn 0.9 V 0.3	12	Zn 0.9 Co 0.5 Cr 0.3	14
7	Cu 0.8 Ga 0.3	7				
8	Ti 0.8 Cr 0.6 V 0.6 Ga 0.6 Fe_2O_3 0.3	18				
%*		88%		87%		86%

*% data correlation explained by each association.

Table 17: Comparison of element associations and loadings and percentage of data correlation accounted for by the associations of factor solutions including and excluding Fe_2O_3, Sn and Sr results, and replicate drainage samples.

The minor element associations of the six-factor model of the replicate drainage samples are also shown in Table 17, in order to compare the factor analytical solution of the overall sampling survey with the replicate samples, which were taken during the second field season only over selected areas and analysed by different methods. The general associations between these two factor solutions are similar. There are Pb-Ga, Ti-Cr-V-Ga and Mn-V associations from both sets of drainage data. There are also associations dominated by Cu, Zn, Ni and Cr from both sets of data although the correlated elements in these associations are somewhat different. The main differences include:

(a) the association of cobalt and nickel with copper rather than gallium. This change is probably due to there being relatively few replicate drainage samples from the Copperbelt area, and secondly the relatively weak association of gallium with copper, which it has already been suggested is of doubtful significance, (section 5.2.4),

(b) the association of cobalt and chromium with zinc in the replicate drainage samples is a change from the single element association of zinc. This is probably due to the better zinc analyses of the replicate samples, which gave a continuous near lognormal distribution of values as a result of better discrimination in the background range of values (5-100 ppm). This would lead to the selection of cobalt and chromium in association with zinc if these elements were correlated mainly in the background range of zinc values,

(c) cobalt is missing from the Ni-Cr association extracted from the replicate drainage data. This is probably the result of a weakened nickel, cobalt correlation due to the lack of replicate samples draining the Karroo basalts around Livingstone.

In conclusion, therefore, the elements in the main associations are essentially the same, and the features giving rise to them have, for the most part, been resampled during the second field season.

The minor element data from the rock, and soil samples were factored using the ten elements mentioned above. From ten to two factors were extracted from these sets of data using the Promax primary pattern matrix powered with $K = 2$. The six factor model was selected in both cases firstly because the percentage of data correlation explained, 85% for the rocks and 87% for the soil data, was close to the 88% and 86% of the original and replicate drainage data respectively, and secondly because the six associations were similar to those from the drainage data. A comparison of these selected factor models (Table 18) extracted from the data from the different sample media shows how essentially similar the associations are although there are some differences. The associations, their similarities and differences are described and discussed below.

(i) Titanium and associated elements

An association with titanium as the most important element occurs in all the sample media. Associated elements include Cr, V and Ga in the factors extracted from the drainage sediment data, and Cr, V and Zn from the rock data. Titanium is extracted on its own in the factor solution from the soil data. Schistose and argillaceous rocks from both Basement and Katangan units have the highest mean R-scores in the Ti-V-Zn-Cr factor of 0.5 and greater. The siliceous schists have values of 0.2 or greater (Table 19). All other lithologies have negative mean R-scores. This substantiates

Rocks			Soils			Drainage Sediment (Original Sampling)			Drainage Sediment (Replicate Sampling)		
Element	Loading	% correlation accounted for	Element	Loading	% correlation accounted for	Element	Loading	% correlation accounted for	Element	Loading	% correlation accounted for
Ti V Zn Cr	0,9 0.5 0.3 0.3	14	Ti	1.0	11	Ti Ga V Cr	0.8 0.6 0.6 0.5	21	Ti Cr V Ga	0.9 0.6 0.5 0.3	17
Pb Zn	1.0 0.5	12	Ga Pb Zn	1.0 0.3 0.3	13	Pb Ga	1.0 0.4	12	Pb Ga	1.0 .06	14
Ni Cr	0.9 0.5	14	Cr V Ni Mn	1.0 0.5 0.3 0.3	16	Ni Co Cr	0.9 0.8 0.5	22	Ni Cr	0.9 0.4	11
Cu	1.0	11	Cu Ni	1.0 0.4	14	Cu Ga	0.8 0.4	10	Cu Co Ni	0.9 0.6 0.4	16
Mn Co Zn	0.9 0.7 0.4	17	Mn Pb V	0.8 0.7 0.3	14	Mn V	0.9 0.3	12	Mn V	0.9 0.6	14
Ga V Cr	0.9 0.6 0.5	17	Co Zn Ni V	0.9 0.8 0.5 0.3	19	Zn	1.0	10	Zn Co Cr	0.9 0.5 0.3	14
otal % correla- ion accounted or		85			87			87			86

Table 18: Comparison of minor element associations extracted from rock, soil and drainage sediment data by R-mode factor analysis, with element loadings and percentage data correlation accounted for by the Varimax orthogonal solution

Geology Factors	Basement Complex						Katangan System			
	Basic rocks	Pegmatites	Granites & Gneisses	Quartzites	Schists	Siliceous Schists	Lower Roan Siliceous Schists	Carbonates	Lower Roan & Mwashia Argillites & Schists	Kundelunga Siliceous Schists
Ti-V-Zn-Cr	-.2	-1.7	-.3	-.3	+.5	.3	.4	-.6	.6	.2
Pb-Zn	-.2	1.4	.6	-.2	.2	-.2	-.6	-.5	-.5	-.3
Ni-Cr	.7	.3	-.2	-.6	.1	.1	.4	.4	.05	.7
Cu	.8	-.6	-.04	-.3	-.04	-.3	.2	-.2	.5	-.5
Mn-Co-Zn	.6	-.7	.1	-1.0	.03	-.7	.02	.6	.1	.3
Ga-V-Cr	.8	-.8	-.3	-.8	.7	-.03	-.1	-.7	.5	.4
No. of samples	23	10	88	21	50	45	21	30	39	14

Table 19: Mean R-scores of rock samples of differing stratigraphy and lithology.

the original interpretation that the Ti-Cr-V-Ga association extracted from the original drainage data was a reflection of underlying schistose or argillaceous rocks.

The reason for the slightly different associations between the titanium factors extracted from the different sample media is not entirely clear although the following possible explanations are suggested. Zinc, which is associated with the titanium factor from the rock data, can be expected to be incorporated in biotite, which is a common mineral in schistose rocks (Rankama and Sahama, 1949). In the secondary environment, however, zinc is one of the most mobile of the elements and therefore most likely to be depleted in the drainage sediment compared to the other elements. The reason for the lack of gallium in the titanium association extracted from the rock samples is more apparent than real. The five factor solution of the rock data combines V-Ga-Ti-Cr into one association with loadings of 0.8, 0.8, 0.8 and 0.6, respectively. The Ga-V-Cr association extracted from the rock data has similarly high mean R-score values of 0.5 or greater in schistose or argillaceous rocks but has its highest mean R-score value of 0.8 from basic rocks. Clearly the elements in these two associations are common to argillaceous or schistose units. Their separation suggests two mineral phases both common in argillaceous rocks of which the mineral represented by the Ga-V-Cr association is also to be found in basic rocks. In the secondary environment these mineralogical differences, however, are reduced by the preference of these elements for the hydrolyzate (clay) sediments. This preference is reflected in their association in a single Ti-Cr-V-Ga factor.

The lack of associated elements with the titanium factor extracted from the soil data is probably due to two features: (a) the soils in general tend to be leached of clay minerals and the mobile elements. Therefore, elements which are included in titanium bearing resistate minerals such as ilmenite and rutile will tend to be enriched in preference to the other elements in more readily weathered and leached minerals, and (b) the titanium analyses of the soil samples have a considerable number of samples above the detection limit. This has resulted in a truncated frequency distribution with some 33% of the samples with values above the detection limit with a value of 22,000 ppm for the sake of calculating the correlation coefficients. This has possibly led to some correlation coefficients of questionable statistical significance.

Despite these reservations, out of 16 randomly chosen soil samples with titanium factor scores of 0.5 or greater, 14 are from soils overlying schistose units, and one is from soils overlying a basic unit and one sample is overlying granitic rocks.

The correspondence of the high Ti-V-Zn-Cr R-scores of schistose rocks, and the general similarity of this association to the Ti-Cr-V-Ga association from the drainage data, shows that the initial interpretation of this factor to be correct. The lack of a comparable association from the soil data indicates the greater redistribution of the elements in the soil than in the drainage sediment.

(ii) Lead and associated elements

An association with lead as the dominant element is extracted from the data from both the rock and the drainage sediment samples.

Zinc is associated with lead in the factor from the rock data and gallium in the factor from the drainage sediment data. Gallium associated with weakly loaded lead and zinc appears a comparable factor extracted from the soil data. Granite and granite gneiss samples have the highest scores in the Pb-Zn association (Table 19). The association of lead with zinc in granites is not a likely combination, since zinc cannot be incorporated in significant amounts in the minerals of normal igneous granites (op. cit.). The Basement granites are, however, mostly gneissic with a fair proportion of biotite and are probably often of metasomatic origin. Biotite can hold a considerable amount of zinc and metasomatic plagioclase can hold up to 60 ppm zinc, whilst lead is known to be high in most granitic rocks (op. cit.). Therefore, it would seem that the Pb-Zn association extracted from the rock data is a geochemically meaningful factor.

The explanation for the different elements associated with lead in the factors extracted from the drainage and soil data is not entirely clear. The most likely explanation lies in the redistribution of these elements in the secondary environment. The more highly mobile zinc is leached away in the dambos in preference to lead and gallium, and both lead and zinc are leached away in the soils in preference to gallium which tends to accumulate with aluminium. Despite these differences, out of 19 randomly chosen soil samples with Ga-Pb-Zn association R-scores greater than 0.5, 15 are overlying Basement granite or gneiss and 4 are over the Basement schistose units.

Although the lead factor associations extracted from the different sample media vary somewhat, these results confirm the original interpretation that the Pb-Ga association extracted from the drainage data reflects the occurrence of granitic rocks within the catchment area.

(iii) Nickel, chromium and associated elements

Elements which occur largely in the mafic minerals are extracted as associations from the data of all the sample media. Nickel and chromium are usually dominant elements in this factor. Cobalt has a high loading in the Ni-Cr association extracted from the initial drainage data, and vanadium and manganese are included with the strongly loaded chromium and lesser loaded nickel association extracted from the soil data.

Basic rocks have the highest R-scores in the Ni-Cr association (Table 19). This tends to confirm the interpretation of the Co-Ni-Cr association, extracted from the initial drainage data, as reflecting basic rocks. The difference between these two associations is probably due to the initial drainage sediment samples including a number of samples from streams draining the Karroo basalts, which were particularly high in cobalt, whilst no Karroo basalts were included amongst the rock samples. The comparable factor extracted from the replicate drainage samples is an Ni-Cr association with almost identical loadings to the rock sample association (Table 18).

A comparable factor extracted from the soil sample data is a Cr-V-Ni-Mn association with loadings of 1.0, 0.5, 0.3, 0.3, respectively. The differences between this association and those extracted from the rock and stream sample data is probably due to the redistribution of these elements by the soil forming processes over basic rocks. Chromium and vanadium will tend to be enriched, firstly because chromite, ilmenite and/or magnetite will accumulate as resistate minerals in the soils and chromium and vanadium tend to be held in these minerals and, secondly, because they are closely associated with iron and aluminium which tend to be enriched in tropical soil profiles. Manganese would also be expected to be enriched because the high pH of soils overlying basic rocks leads to its oxidation and precipitation. Manganese and iron, once they are oxidised, will tend to form insoluble pellets which will then behave in much the same way as primary resistate minerals. Nickel as the most mobile of the elements in the association would be the most likely element to be leached from the soils although its mobility will be reduced by the high pH conditions. The relation of this minor element association in the soils with underlying basic rocks is substantiated by the fact that out of 19 randomly selected soil samples with Cr-V-Ni-Mn association R-scores greater than 1.0, 12 have underlying basic rocks. The remaining 7 are distributed equally over the other rock types encountered in the field area.

In conclusion, therefore, the Ni-Co-Cr and the Ni-Cr associations extracted from drainage data correspond to the Ni-Cr association extracted from the rock data, and reflect the presence of basic rocks. A similar Cr-V-Ni-Mn association has been extracted from the soil data, however, secondary environmental effects have complicated the original primary association with the inclusion of vanadium and manganese.

(iv) Copper and associated elements

A factor in which copper is selected as the dominantly loaded element has been extracted from the data from each of the sample media (Table 18). The associated elements, however, are different. Possible reasons for the different associations between the initial and replicate drainage sample data has already been discussed in the earlier paragraphs of this section. The single element copper factor extracted from the rock data suggests that copper has no strong affinity for the other elements in the primary environment. According to Rankama and Sahama (1949) this is to be expected since copper's strong affinity to sulphur precludes any association with the common rock forming silicates, with the exception of the mafic minerals. Therefore, the Cu-Ga association extracted from the initial drainage sample data is most probably the result of a secondary environmental association. The reason for the Cu-Ni association extracted from the soil data is not known. Presumably it reflects, to some extent, the similar behaviour of these two elements in the soil profile.

Rock samples with the highest scores in the copper factor include basic igneous rocks and the lower units of Katangan argillaceous and schistose lithologies (Table 19). The high copper factor scores from basic rock samples are to be expected because of their normally high copper content. The high copper content of the schistose and argillaceous units of the lower Katangan System are markedly higher in copper R-score value than the Basement or Upper Katangan Kundelunga schists and argillites (Table 19). This demonstrates the affinity of copper for these Katangan units despite the fact that most of these samples came from the Lusaka area rather than the Copperbelt. Not only does this suggest the pervasive stratigraphic association of copper for the Lower Katangan argillaceous units, but it also helps to substantiate the present tenuous correlation of the Copperbelt Katangan units with similar lithologies in the Lusaka area.

The regional distribution of copper values has already been shown to reflect the Copperbelt and Lusaka East metallogenic provinces in addition to basic rocks. The fact that copper can be separated from the mafic elements in a factor analytical solution confirms that features other than basic rocks are controlling the copper distribution.

(v) Manganese and associated elements

Associations in which manganese is selected as the dominantly loaded element are extracted from data of each of the sample media (Table 18). The associated elements include vanadium from the stream sediment data, lead and vanadium from the soil data and cobalt and zinc from the rock sample data. The differences between these factors is largely due to manganese associations extracted from the soil and stream sediment samples being controlled by secondary environmental features, whereas the Mn-Co-Zn association extracted from the rock data is controlled by lithology.

The highest mean Mn-Co-Zn R-scores occur in samples from basic and carbonate rocks (Table 19). There is no regional variation of higher values in the south compared to the north such as are encountered in the stream sediment and soil samples.

Although stream sediment samples draining basic and carbonate rocks do have higher values than samples draining other rock types, the general regional trend with higher values in the south compared to the north are added to these local trends.

The Mn-Pb-V association extracted from the soil data shows similar enhanced R-score values in the south compared to the north as the drainage sediment data. The inclusion of lead with manganese in this association is probably a reflection of two features. Firstly, many of the granitic rocks in Zambia are probably more intermediate in composition, including many diorites and granodiorites, which characteristically have a relatively greater proportion of manganese and lead than other rock types (Rankama and Sahama, 1949). Clearly, more of the soils over these rock types have been sampled than the rocks of the same type to bring out this association. Secondly, manganese is probably concentrated in the soils overlying granitic rocks because they tend to be coarser sands than over most other rock types allowing for the greater aeration and oxidation to the insoluble manganese oxides. Lead, which is already enhanced in the granitic rocks is probably scavenged to some extent by this manganese oxide thus further increasing the correlation of the two elements. The elutriation of the manganese in the wet acid environment of the dambo has prevented this correlation being established from the drainage sediment data.

In conclusion, the sympathetic increase southwards of the R-scores of the manganese associations extracted from both the soil and drainage sediment data, and the complete lack of the same regional variation from the manganese association extracted from the rock data demonstrates the climatic control over the manganese distribution in the secondary environment.

(vi) Sixth factor associations

The sixth factor extracted from the data of each of the sample media have rather different minor element associations. The possible implications of the Ga-V-Cr association extracted from the rock sample data has already been discussed in an earlier section (i), and related to the Ti-V-Zn-Cr association and argillaceous and basic rock types. The reasons for the zinc associations extracted from the drainage sediment data and the Co-Zn-Ni-V association extracted from the soil data remains problematic, although explanations can be suggested, such as secondary environmental redistribution or a primary association that has not been recognised. The latter alternative is supported to some extent by the extraction of Co-Zn with loadings of 0.9 and 0.5, respectively from the rock data by the seven factor model.

The zinc distribution extracted from the drainage data, which was related to Basement rock units (section 5.2.3(iv)) is not reflected in the associations extracted from the rock or soil data. The single element variation of zinc in the rock samples give some indication that zinc is higher in Basement units which have an average of 30 ppm Zn compared with Katangan units which have an average of 23 ppm. Individual units in different areas, however, show a much greater variation (Table 15(a)). The regional variation of zinc in the soil data shows both the Kafue to Choma and the Broken Hill areas to be relatively high which agrees with the distribution of zinc in the drainage sediments (Table 16(a)). Lusaka East soils, however, have a surprisingly low average zinc value which does not corroborate the drainage data. The explanation for these differences is probably the lack of a suitable two-dimensional soil and rock sample grid of comparable sampling efficiency to the drainage data. Certainly, the lack of a zinc association being extracted from the rock and soil data is due firstly to the lack of large zinc variation and secondly, to the better zinc analysis which did not result in a large percentage of samples being below the detection limit.

5.3.3 Implications of factor analytical solutions

The similarities between the minor-element associations extracted from the data from the different sample media by factor analysis demonstrates:

(a) that drainage sediments and to a lesser extent soils have a minor element content which reflects the primary geochemistry within the provenance of the sample,

(b) that drainage sediments have a closer minor element content to the primary geochemistry than the soils. This is indicated by the closer correspondence of the factor associations extracted from drainage sediment data with those from the rock data, than those extracted from the soil data. This is probably the result of the continuous elutriation of the clays and minor elements in the Zambian plateau soils, whilst in the drainage sediments of the dambo type there is a considerable accumulation of clays which will tend to adsorb the minor elements and thus reduce their mobility and possible redistribution. In the escarpment areas where there are active stream sediments there is no clay fraction. These active streams are, however, mostly eroded to bedrock and much of the sediment is composed of weathered rock fragments and the minor elements will have had less of an opportunity at redistribution even in these sediments than in the soils, and

(c) that the features controlling minor element distributions are considerably easier to evaluate from the factor analytical associations and R-score patterns than trying to interpret single element distributions. This has resulted firstly by a reduction in the number of variables to consider, and secondly by the attention that is drawn from the combination of elements into associations, to the possible presence of primary or secondary features which are known to have high contents of the particular elements in an association.

5.4 CONCLUSIONS ON PROVINCIAL GEOCHEMICAL RECONNAISSANCE

The most important general conclusion from this study is that it is possible from very wide interval geochemical drainage sampling to gain useful information of the primary geochemistry of a large area. In particular, it has been possible to define:

(a) the Copperbelt metallogenic province as an area with an enhanced copper background in the drainage sediments which is due to an increased copper content in all the bedrocks and/or a greater incidence of minor copper mineralisation;

(b) the Lusaka metallogenic district as an area with enhanced copper background in the drainage sediments which is probably due to the increased incidence of minor copper mineralisation;

(c) the Choma tin belt as an area with enhanced tin background which is due to an increased tin content of the rocks within the metallogenic district.

Analyses of rock and soil samples have shown that the minor element content of drainage sediment samples of streams with small catchment areas (less than, or equal to, 10 square miles) has a closer relationship to the primary geochemistry in the upstream catchment area than soil samples. Most of the minor element regional variations from the drainage sediment data with the exception of copper, tin, manganese, ferric iron and to a lesser extent vanadium, could be related to different lithologies. The distribution of manganese and ferric iron in the sediments and soils were related to rainfall variations, having low values in the high rainfall area in the north, and also the basic and carbonate rocks.

R-mode factor analysis on the drainage sediment, rock and soil data has been a useful aid in interpreting the multi-element date in terms of the features controlling their distribution by combining the minor elements into associations. The calculation of R-scores for each association on each sample has made it possible to map and contour these associated elements as single parameters and thus indicate the provenance of controlling features. In particular, three of the minor-element associations extracted by factor analysis have been related to lithology namely: (a) a Ti-Ga-V-Cr association to schists, (b) a Pb-Ga association to granites and granitic rocks, and (c) a Co-Ni-Cr association to basic rocks. The Cu dominated association was related to the copper metallogenic province. The Mn-V association was related to secondary environmental controls and to carbonate and basic rocks. A zinc association extracted from the original drainage data remained problematic.

Moving average analysis has shown itself to be a useful technique for smoothing the data to bring out broad scale background variations of the minor-elements. This knowledge of background variations would prove to be useful when further more detailed geochemical sampling in an area is carried out. The method could easily be adapted to give a moving threshold map.

CHAPTER 6

INTERPRETATION OF REGIONAL GEOCHEMICAL RECONNAISSANCE RESULTS USING R-MODE FACTOR ANALYSIS

6.1.0 INTRODUCTION

Interpretation of minor-element geochemical reconnaissance data in Zambia, collected by the mineral exploration companies has been mostly limited, until the present, to a selection of anomalous samples. Some regional interpretations have been attempted, but apart from combining two elements into ratios it has been impossible: (a) to combine or relate the element data or, in other words, show inter-element correlations in a convenient map form, or (b) to identify the controlling features of the geochemical data from the element variations or correlations.

Geochemists and geologists involved in mineral exploration in Kadola and Lusaka East areas have been able to recognise certain areal variations of the minor-elements in the stream sediment geochemical data. In some cases these areal variations can be related to already known geological features, but it has not been possible to identify the geological features from the geochemical data. For example it has been possible to see in the Kadola area data a general regional increase in copper, chromium, gallium lead and nickel of about 1.5 - 2 fold in the east and north east of the field area, and a manganese, titanium and vanadium increase by 1 to 2 fold in the central and western half of the field area compared to the east. These variations seem to reflect background differences between the Basement units outcropping in the east and north east of the area and Katangan units in the west and central part of the field area (Wilding, I.P. pers. comm.). It is impossible, however, to define these areas in detail, and determine the cause of these variations without previous knowledge of the geology.

Similar interpretations of geochemical data from Lusaka East area are possible. For example, enhanced values of copper, cobalt, nickel and zinc occur over basic rocks. This interpretation was made by relating the contoured values of each of the elements to the geological map (Downey, J. pers. comm.). Due to the number of values to be considered and the variability of the data, contouring was a laborious process. It was also extremely difficult to consider the variations of more than one element at a time. No other minor element variations could be related to the known geology and apart from basic rocks it was not possible to interpret the geology from minor-element correlations.

In both the Kadola and Lusaka East areas the geology is a complex mixture of lithologies as has been described in sections 3.2 and 3.3. The minor-element content of drainage sediments derived from the differing lithologies might be expected to vary, and their composition will be complicated by the mixing of sediments from different sources upstream from the sample point. The selection of anomalous samples, possibly related to mineralisation, in areas of these changing background variations is not easy particularly where geologic control is poor. In Kadola and in parts of Lusaka East outcrop is poor due to deep over-burden and lack of relief.

Kadola and Lusaka East differ considerably in both geology and secondary environment. Kadola is underlain mostly by Katangan units with some Basement units in the east and north east, and is situated on the main plateau and is therefore flat with broad dambo drainages. Lusaka East area is underlain mostly by Basement granites and gneisses and high grade metamorphic units, and being on the edge of the escarpment is comparatively rugged with streams as well as dambo type drainages.

The object of this study is, therefore, to evaluate the use of R-mode factor analysis as a means of identifying the controlling features from the multi-element data of drainage sediment samples, in terms of the differing lithologies, mineralisation and secondary environment, which occur in the two areas.

6.2. KADOLA AREA

6.2.1 Relationship between minor-element content of drainage sediments and geology

From the previous section it appears likely that background minor-element values are in part controlled by the geology, The samples were, therefore, separated into seven groups based on the geologic unit which occurs within the upstream catchment area from the sample point. Mean values and ranges at standard deviations limits (table 20) show marked variations between some of the units.

A striking variation is the 2-3 fold higher cobalt, copper, manganese, nickel, titanium and vanadium, and 7-8 fold higher chromium associated with the units mapped as acid crystalline rocks in the north compared to similar units in the south. Lead, on the other hand, is 3 fold higher in the southern acid crystalline compared to the same unit in the north. There is, however, an increase of lead content in all the acid crystalline units of 2-5 fold relative to other units. Other variations are somewhat less marked. Copper and manganese are enhanced 1.5 to 2 fold and titanium about 1.3 fold above the overall means in stream sediments draining the Muva quartzite and schist units. Manganese and vanadium are enhanced 2 fold and nickel and cobalt 1.3 fold over Kakontwe limestone compared to the overall means.

It is clear from these results that there is a significant variation of minor element content in stream sediments draining different geologic units. The corollary, therefore, should be that

	Basement Complex					Katangan System		
	Acid crystalline in north	Acid crystalline in east	Acid crystalline in south	Undifferentiated Basement	Muva schists and quartzites	Lower Roan quartzites	Kakontwe Limestone	Overall mean and standard deviation range
Co *GM $^+$Range	24 8-70	17 7-45	6 3-13	19 6-65	18 5-80	22 6-75	25 8-80	19 14-25
Cr	45 23-85	65 22-155	6 2-21	22 6-75	40 20-90	14 5-40	40 13-130	35 16-60
Cu	50 25-95	40 19-28	9 3-25	14 6-33	60 19-200	18 7-46	21 7-60	29 12-45
Fe_2O_3 %	1.6 1.0-2.5	1.8 1.1-3.0	1.2 .7-1.8	1.5 .9-2.6	2.1 1.4-3.3	1.3 .7-2.6	2.2 1.1-4.4	1.7 1.3-2.1
Ga	12 4-35	17 9-35	9 4-19	8 2-24	8 4-18	5 2-14	7 2-24	9 6-13
Mn	110 26-440	170 75-380	55 11-260	45 9-240	160 70-380	65 22-200	240 65-880	120 45-190
Ni	67 33-135	70 30-164	17 7-39	42 54-104	66 26-162	45 20-106	66 25-176	53 36-70
Pb	8 3-20	14 8-27	25 13-50	3 1-9	5 2-11	5 2-13	4 1-10	9 2-16
Ti	3400 1600-6900	3800 2000-7400	1600 900-3000	3000 1400-6500	4300 2000-9300	2300 1100-4800	3700 1000-13000	3200 2900-3500
V	40 21-75	50 26-95	23 8-60	45 16-120	45 15-120	30 11-80	100 35-280	50 25-70
No. of samples	46	23	47	41	31	29	17	232

*Geometric means; $^+$Range at the single standard deviation limit
Units are in ppm

Table 20: Mean element content and single standard deviation ranges of stream sediments draining major geologic units in Kadola.

R-mode factor analysis will define element associations from which it is possible to identify the various bedrocks. The contoured R-score values can then be used to classify the samples in terms of these associations and indicate the provenance of the controlling features.

6.2.2. Results of R-mode factor analysis of drainage sediment data

R-mode factor analysis of the multi-element data, using ten elements, namely cobalt, chromium, copper, gallium, ferric oxide, lead, manganese, nickel, titanium and vanadium, was carried out in order to clarify element associations. Loadings on elements in each factor in factor models extracting from three to eight factors are shown in table 21. Elements with loadings of below 0.3 are not included in a factor since it was found that mean values of elements with loadings below 0.3 did not always have a consistent, reliable variation with changes in R-score value.(tables 23 (a-e)).. The variation of element contents with R-score class will be discussed with each factor. The five factor model was chosen because the extracted associations appeared explainable in terms of the known geology and secondary environment, and 85% of the inter-element correlation is explained. In addition the communalities of each element in the five factor model are all greater than .71 (table 22). That is to say, a minimum of 71% of the inter-correlation of vanadium, and a maximum of 95% of the intercorrelation of lead and manganese are explained by the five factor model. (N.B. the communality is a measure of the amount of intercorrelation of each element that is accounted for by any particular factor model. A communality of 1.0 would imply that all the intercorrelation of that element had been explained).

Factor Model Factor association	3 Element Loading	4	5	%correlation accounted for by each factor	6	7	8
1	Cr .9 Ti .8 Ni .8 Co .7 V 7 Cu .6 Ga .6	Ti .9 V .6 Cr .6 Ni .5 Ga .4 Co .3	Ti .9 V .6 Cr .6 Ni .5 Ga .4 Co .3	27%	Ti .9 Cr .4	Ti .9 Cr .4	Ti 1.0
2	Pb 1.0 Ga .6	Pb 1.0 Ga .5	Pb 1.0 Ga .5	13%	Pb 1.0 Ga .6	Pb 1.0 Ga .5	Pb .8 Ga .4
3	Mn .9 Fe_2O_3 .8 Co .3 V .3	Mn .9 Fe_2O_3 .7	Mn .9 Fe_2O_3 .3	11%	Mn .8 V .3	Mn .9	Mn 1.0
4		Cu .9 Ni .6 Co .6 Cr .5 Ga .4	Cu .9 Ni .4 Cr .4 Co .3	16%	Cu .9 Ni .3 Cr .3	Cu .9 Cr .3	Cu 1.0
5			Fe_2O_3 .8 Co .6 Ni .3 V .3 Ga .3	18%	Fe_2O_3 .8	Fe_2O_3 .9	Fe_2O_3 1.0
6					Co .8 V .8 Ni .6 Cr .5 Ga .5	Co .9 Ni .6 Cr .3	V 1.0 Ga .3
7						V .8 Ga .3	Co 1.0 Ga .3
8							Cr .9 Ni .8
%correlation accounted for by each factor	74%	80%	85%		90%	94%	96%

Table 21: Element loadings and associations of different factor models extracted from geochemical drainage reconnaissance data of Kadola (481 samples, 10 element)

Factor models / elements	8	7	6	5	4	3
Co	.98	.94	.83	.79	.70	.67
Cr	.93	.84	.84	.84	.83	.84
Cu	1.00	.98	.94	.92	.81	.56
Fe_2O_3	1.00	1.00	.97	.85	.72	.72
Ga	.88	.88	.88	.88	.83	.85
Mn	.99	.99	.97	.95	.79	.77
Ni	.92	.87	.83	.83	.83	.81
Pb	.97	.96	.95	.95	.95	.95
Ti	1.00	.97	.96	.83	.81	.65
V	.98	.98	.82	.71	.71	.64

Table 22. Communalities of the elements in the different factor models from the rotated factor matrix.

The associations are in some respects similar to those extracted from the provincial data and, therefore, their controlling features were throught to be similar. That is to say the Ti-V-Cr-Ni-Ga-Co association was related to the schistose and argillaceous units, the Pb-Ga association to the granitic units, Mn-Fe_2O_3 association with possible secondary enrichments of these elements. The inclusion of Ni-Cr-Co in the association dominated by Cu was considered to indicate that basic rocks were in close relation to copper mineralisation. The Fe_2O_3-Co-Ni-V-Ga association was related to laterite which commonly occurs in the soils in the Kadola area.

6.2.3 Description and discussion of R-score distributions

(i) Ti-V-Cr-Ni-Ga-Co Association

This association, which accounts for most of correlation between the elements (27%) is dominated by Ti-V-Cr with high loadings associated with more weakly loaded Ni-Ga-Co. This association persists as a group of elements from the 3 to 5 factor model. When six factors are extracted Co-V-Ni-Ga forms a second association which includes Cr but leaves a Ti-Cr association. The association is, therefore, a fairly consistent grouping of elements.

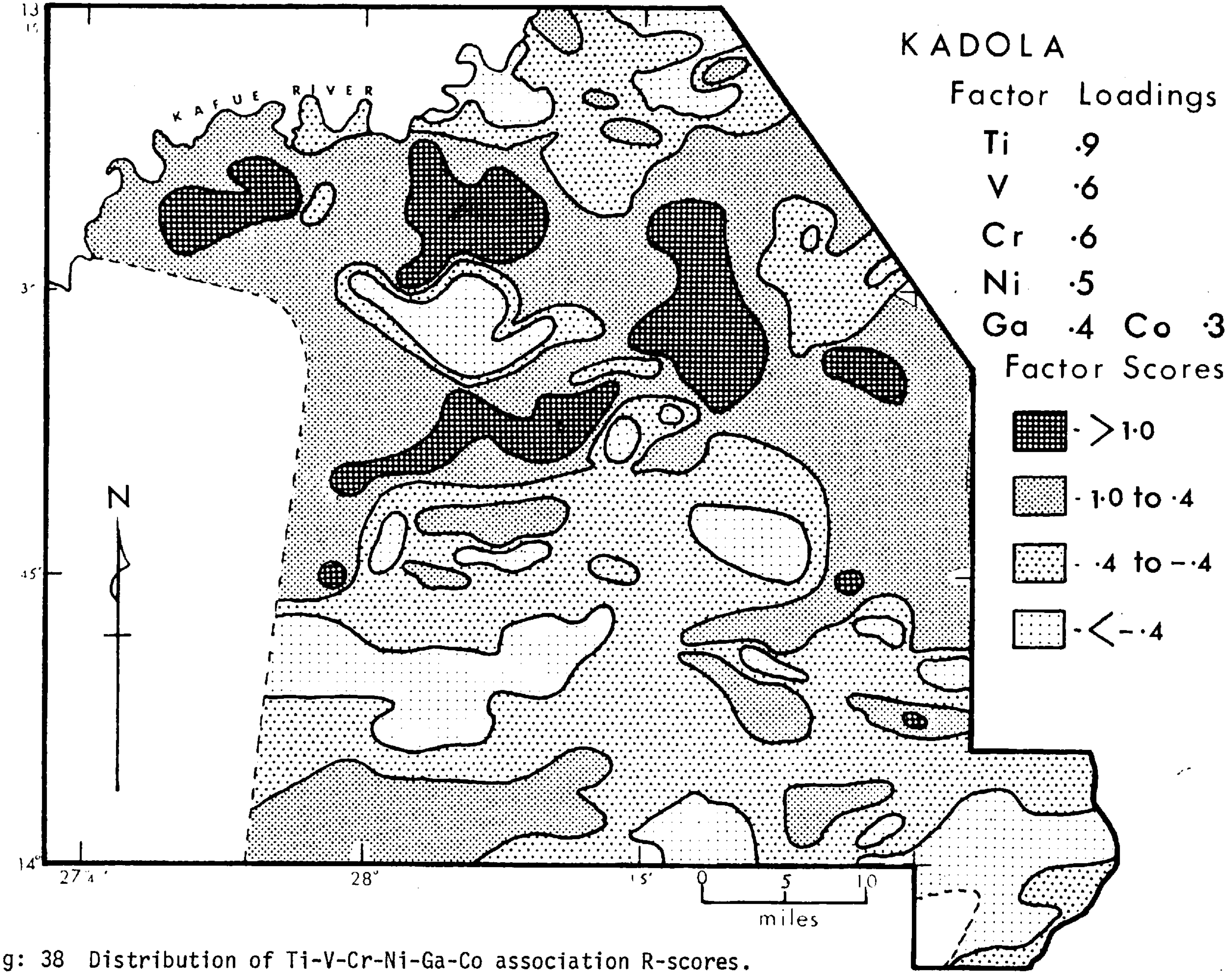

Fig: 38 Distribution of Ti-V-Cr-Ni-Ga-Co association R-scores.

The R-score values were plotted and contoured (fig. 38). The contour intervals for this association and the other factor associations were chosen, firstly on the basis of the distribution of the R-score values, this is to say contours were omitted if they tended to closely parallel previous contours, and secondly on the basis that the R-score contour intervals must be reflected by a significantly large change in element level of the elements with loadings of greater than 0.3.

The mean element values in table 23 (a) show that there is normally a consistent and fairly large drop with R-score value, and that the change in element values at the selected R-score contour intervals are significant in terms of the precision levels, for all the elements with loadings of 0.3 and greater.

The contoured R-scores show that samples with R-scores greater than 1.0 tend to lie in a semi-circle opening westwards, around the Kakontwe limestone (fig. 38). These high R-scores are mostly over Mwashia shale and Lufubu schist units, however, the southern side of the semi-circle and parts of the large east central pattern overly areas mapped as Kakontwe limestone. R-scores tend to be low, below -0.4, over the main central portion of the Kakontwe limestone, and below 0.4 over Basement units other than the Lufubu schists. R-scores are mostly below -0.4 over the acid crystalline units and are usually below -1.0 and -2.0 over the acid crystalline unit in the south.

The correspondence of the high Ti-V-Cr-Ni-Ga-Co association R-scores with the Mwashia shale and Lufubu schists indicates that this group of elements does in fact reflect the presence of argillaceous and schistose units as suggested earlier. The high R-scores patterns over the Kakontwe limestone, therefore, are anomalous and suggest either incorrect geological mapping or else a facies change within the Kakontwe

R-Scores

Element	Loading	1.0	0.4	0.0	-0.4	-1.0	-2.0	
Ti	.9	8000	6400	5200	3100	1800	940	400
V	.6	190	100	50	32	27	30	11
Cr	.6	95	75	35	21	23	6	2
Ni	.5	140	110	65	40	50	18	7
Ga	.4	24	15	10	7	6	3	1
Co	.3	55	45	30	12	16	7	5
Mn	.1	200	180	150	80	140	110	45
Cu	.02	35	40	29	20	25	12	5
Fe_2O_3	-.02	2.3	2.4	1.8	1.3	1.6	1.3	0.9
Pb	-.04	6	6	8	7	5	6	3
No. of samples		21	29	31	23	26	15	13

(all units in ppm except Fe_2O_3 which is a %)

Table 23: Mean element values of samples with varying R-scores of the associations extracted from drainage reconnaissance data of Kadola.

(a) Ti-V-Cr-Ni-Ga-Co association

limestone unit.

(ii) Pb-Ga association

The second factor is an association of lead and gallium with loadings of 1.0 and 0.5 respectively. This association occurs in all the factor models from three to eight which indicates that it is a very dominant association. It accounts for 14% of the data correlation. The variation in lead value with R-score level (table 23(b)) is often better than 50% difference between adjacent R-score classes. Gallium decreases considerably considering its low overall range in value, but not by as much as lead. The other elements either show no variation or else an antipathetic relationship with R-score class.

Samples with Pb-Ga association R-scores greater than 1.0 occur mostly in streams draining acid crystalline units (fig. 39). Over the acid crystalline outcrop in the south-east Pb-Ga R-scores tend to be higher, of the order of 1.5-2.0, than over the northern acid crystalline where R-scores tend to be between 1.5 and 0.5. Over the Basement units in general, and in the south-east in particular, Pb-Ga R-scores tend to be higher, in the 1.0 to 0.5 range, than those over the Katangan unit which tend to be in the 0.5 to below -0.5 range. There are two anomalous areas of Pb-Ga R-scores, one with values greater than 1.0 over Kakontwe limestone in the north-west just east of Kashiba, and a large area in the west also over Kakontwe limestone with values between 1.0 and 0.5. The small area, with relatively high R-score values of the former area, and its presence over carbonate rocks indicates possible lead mineralisation. The extensive area of medium to high R-scores over the latter area indicates that it is perhaps underlain by Basement units and not Kakontwe limestone as it is mapped.

The correspondence of the high Pb-Ga R-scores with the acid crystalline rocks confirms the interpretation of this factor.

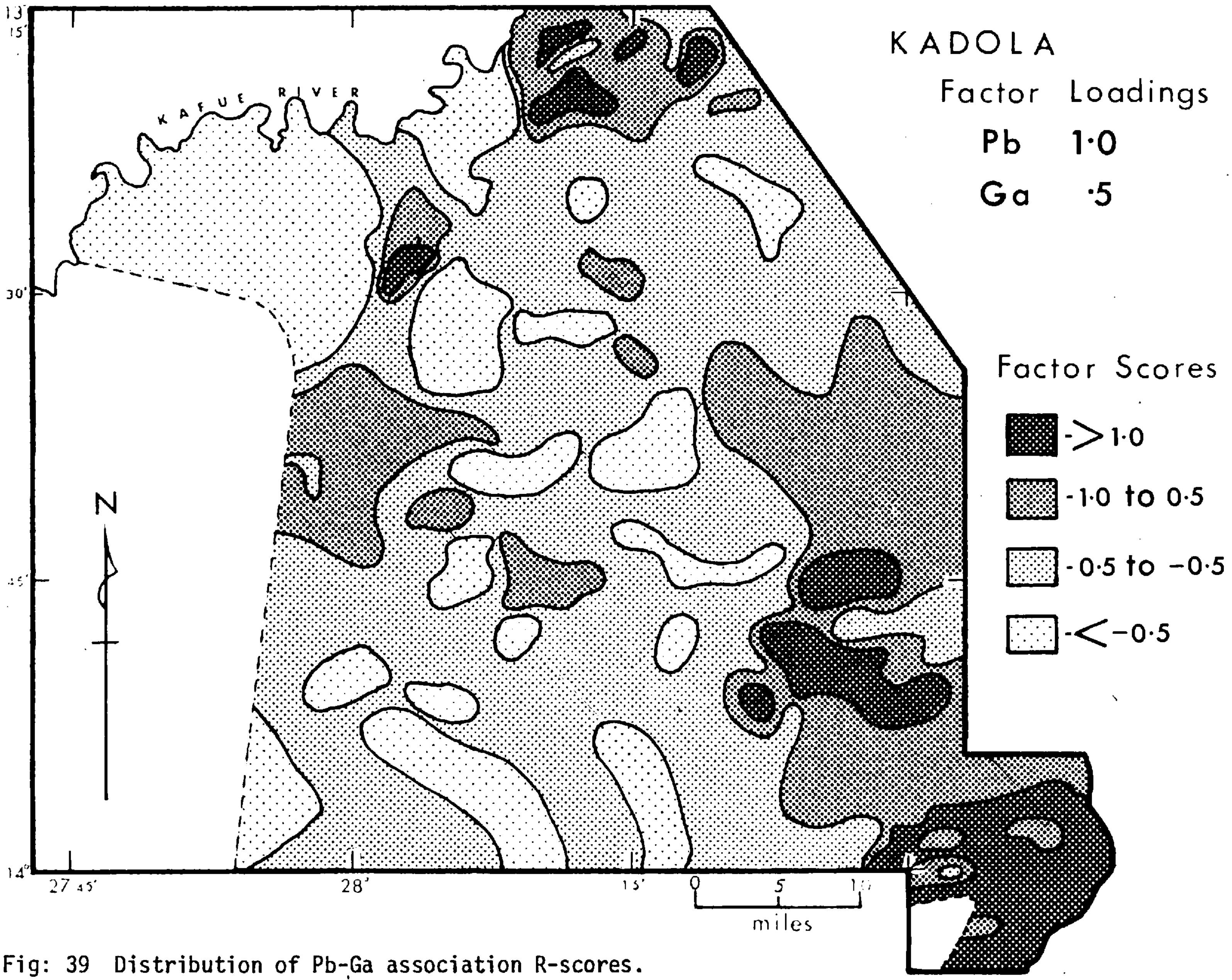

Fig: 39 Distribution of Pb-Ga association R-scores.

		R-Scores						
Element	Loading		2.0	1.0	0.5	0.0	-0.5	-1.0
Pb	1.0	60	25	11	8	5	2	1
Ga	.5	30	27	16	14	7	9	3
Cu	.08	16	35	35	40	23	25	11
Fe_2O_3	.05	1.8	2.0	1.9	1.8	1.9	1.9	1.5
Ti	.05	2700	4500	3900	4800	4300	4200	3000
V	.003	40	65	60	80	55	65	55
Mn	-.01	100	150	210	130	110	150	130
Cr	-.04	22	45	35	60	45	40	22
Co	-.05	11	28	25	27	30	26	14
Ni	-.08	35	60	70	85	75	80	35
No. of samples		6	18	17	29	25	15	26

(all units in ppm except Fe_2O_3 which is a %)

Table 23(b): Pb-Ga association

(iii) $Mn-Fe_2O_3$ association

The association of $Mn-Fe_2O_3$ is controlled largely by manganese with a high loading of 0.9, whilst ferric iron has a comparatively low loading of 0.3. It accounts for 11% of the data correlation, which is the lowest accounted for by any of the associations. In the three and four factor models $Mn-Fe_2O_3$ are also selected as an association although ferric iron has a loading of 0.8 and 0.7 respectively and Co-V with loadings of 0.3 are selected in the three factor model and V with a loading of 0.3 is selected in the four factor model. When five factors are extracted ferric iron separates from manganese to some extent in an association with Fe_2O_3-Co-Ni-V-Ga, and is not significantly loaded with manganese in the seven and eight factor models (table 21). These variations in association extracted by the different factor models suggest that ferric iron is not very strongly correlated with manganese. This conclusion is supported by the variation of element value with R-score level (table 23(c)). Manganese decreases about 50% between the decreasing R-score classes, while ferric iron by only 9% to 20% over a fairly low range of values between 5% and 1% Fe_2O_3 which is considerably lower than the 11.4% to 0.8% range of ferric iron in the Fe_2O_3-Co-Ni-V-Ga association (table 23(a)). These results show that, although $Mn-Fe_2O_3$ have been selected as an association, they do not correlate strongly over the full range of ferric iron values.

Samples with $Mn-Fe_2O_3$ association R-scores greater than 1.0 occur mostly over the north central part of the field area underlain by Kakontwe limestone (fig. 40). This main pattern of high R-scores extends north-eastwards across the lower boundary of the Kakontwe limestone, over the underlying Katangan sediments and the Muva schists and quartzites. There are two other small areas with R-scores greater

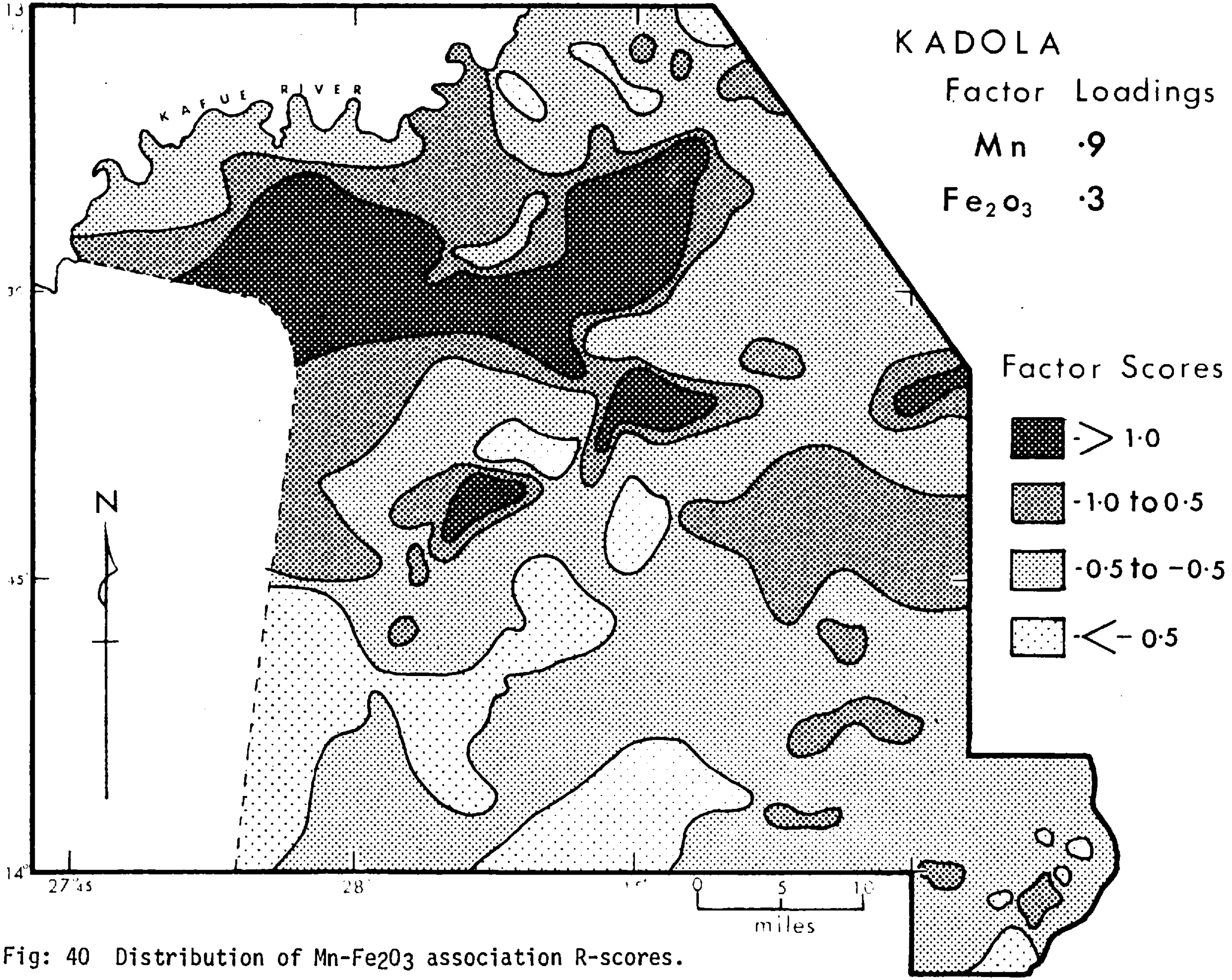

Fig: 40 Distribution of Mn-Fe_2O_3 association R-scores.

R-Scores

Element	Loading	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0	
Mn	.9	1400	880	280	140	80	50	13	4
Fe_2O_3	.3	5.0	3.4	2.0	1.7	1.6	1.2	1.0	1.1
V	.2	85	120	55	55	55	45	30	19
Cu	.1	22	45	35	30	29	17	13	8
Ti	.06	4500	6400	4600	4900	3900	2900	1900	1900
Cr	.05	29	60	35	40	35	22	12	8
Pb	.04	5	8	6	5	8	5	3	4
Ni	.003	60	100	60	60	55	65	45	21
Ga	-.09	6	15	11	9	12	6	4	5
Co	-.1	30	45	20	16	23	23	13	9
No. of samples		7	19	26	26	35	21	20	21

(all units in ppm except Fe_2O_3 which is a %)

Table 23(c): Mn-Fe_2O_3 association

than 1.0 which do not occur over Kakontwe limestone. One is on the eastern central side of the field area over Muva quartzite and schist and the second is just south west of the centre of the field area over undifferentiated Basement units. The remainder of the field area is, with some exceptions, below 0.5 in R-score value. It is significant to note that the Mn-Fe_2O_3 R-scores are surprisingly low, below 0.5 in some places, in the southern part of the area mapped as Kakontwe limestone, which has already been noted to have anomalously high Ti-V-Cr-Ni-Ga-Co association R-scores.

The correspondence of high manganese in drainages over carbonate rocks is to be expected because:

(a) carbonate rocks are likely to have a higher manganese content than most other rock types present in the area, and

(b) manganese is most likely to oxidise, precipitate and accumulate in the drainages over carbonate rocks firstly because of the alkaline conditions, and secondly because the drainages over the Kakontwe limestone tended to be shallow, dry dambos, as described in section 3.2.4, which would also lead to a greater amount of oxidation of manganese than is likely in the wetter more acid dambos over other bedrock types. the low Mn-Fe_2O_3 R-scores over the area mapped as Kakontwe limestone and the values over Muva quartzites and schists, and undifferentiated Basement units must, therefore, be considered as anomalous and due either to incorrect geologic mapping or incorrect chemical analyses.

(iv) Cu-Ni-Cr-Co association

The Cu-Ni-Cr-Co association is dominated by copper with a loading of 0.4, 0.4 and 0.3 respectively. This association accounting for 16% of the data correlation, appears to indicate a fairly strong correlation between the elements since it persists from the four to six factor model with only the addition of gallium in the four factor model and the loss of cobalt in the six factor model (Table 21). In the seven factor model Co-Ni-Cr is separated leaving a Cu-Cr association and in the eight factor model copper is extracted on its own with Cr-Ni and Co-Ga in separate associations. Although there is clearly some correlation of copper with cobalt, nickel and chromium, these separations after the six factor model indicate that there are possibly other features influencing the distribution of cobalt, nickel and chromium which are not common to copper.

The variation of element content with R-score level shows that there is, in general, a significant decrease of the element content with decreasing R-score class (Table 23(d)). There is, however, a reversal in the mean chromium value between the top two R-score classes, greater than 2 and between 2 and 1, and very little nickel or cobalt variation, whilst copper decreases by more than 50%. The mean values of the elements in the association decrease more significantly and consistently between the subsequent R-score classes until the -0.5 to -1.0 class, where there is an increase in nickel and chromium and little decrease in cobalt with the preceeding higher R-score values. These reversals in expected element value with R-score class similarly suggest that there are possibly other features affecting the distribution of these elements besides the one which this factor association reflects.

Samples with high (greater than 1.0) Cu-Ni-Cr-Co association R-scores occur over a well defined area in the north east and eastern edge of the field area (Fig. 41). This area is underlain mainly by Muva quartzites and schists. Two high samples, however, are from

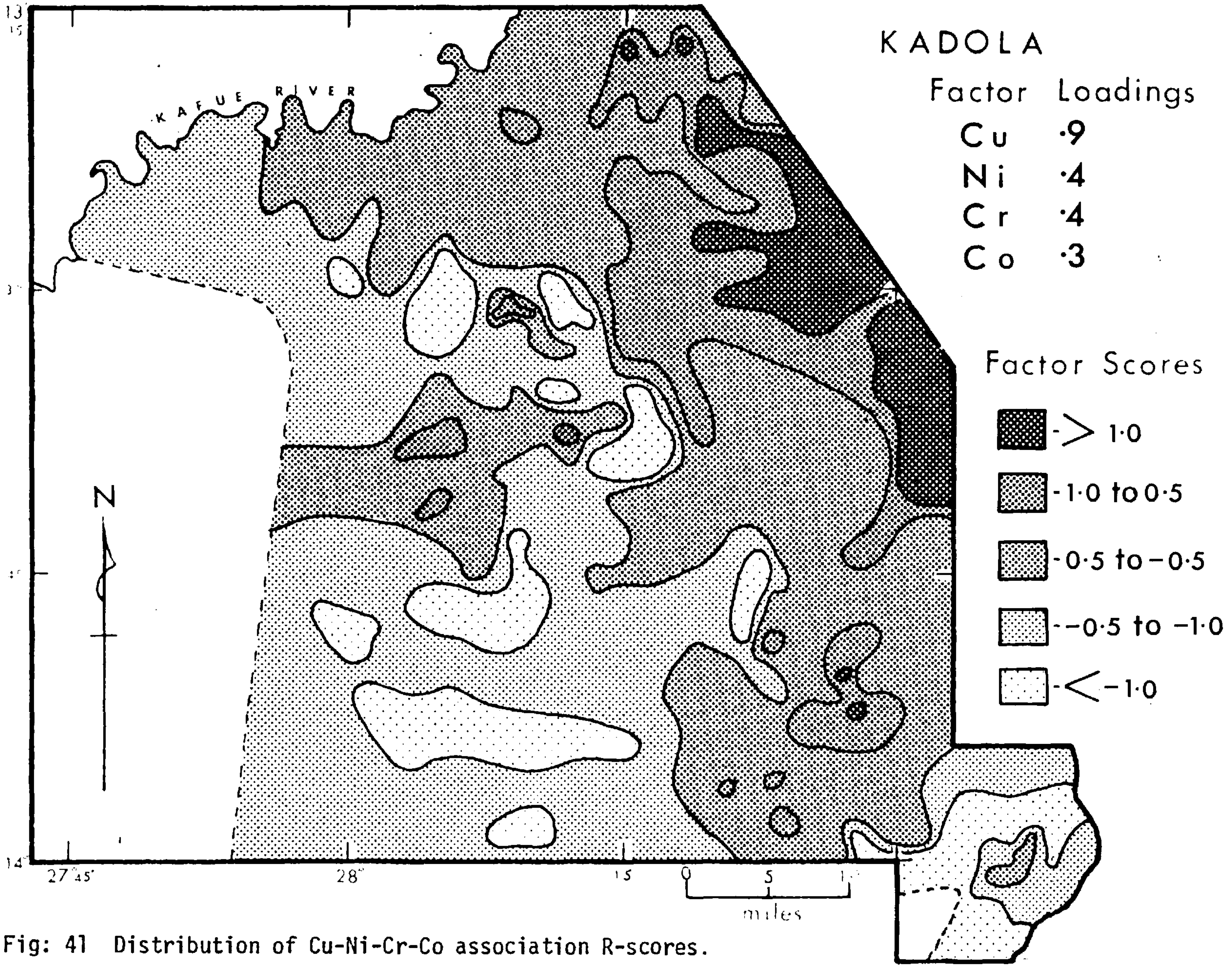

Fig: 41 Distribution of Cu-Ni-Cr-Co association R-scores.

R-Scores

Element	Loading	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0	
Cu	.9	250	110	50	35	20	10	5	1
Ni	.4	180	150	80	70	35	40	18	7
Cr	.4	85	100	55	35	21	23	8	2
Co	.3	85	70	35	18	13	11	6	5
Ga	.2	18	30	12	11	7	7	3	2
Mn	.1	150	260	160	160	90	55	55	27
Pb	-.004	4	12	8	6	6	5	4	4
Ti	-.02	3400	5800	3200	4900	2900	3300	1800	1300
V	-.03	65	110	70	65	45	45	27	9
Fe_2O_3	-.05	2.2	2.5	2.0	1.8	1.6	1.2	1.2	1.0
No. of samples		10	17	20	23	23	21	24	11

(all units in ppm except Fe_2O_3 which is a %)

Table 23(d): Cu-Ni-Cr-Co association

dambos draining the acid crystalline unit in the north, and two are from dambos draining across the Upper and Lower Roan contact near Kadola mineral showing. The rest of the field area is divided more or less in half by the 0.5 R-score contour with R-scores greater than 0.5 to the east and less than 0.5 to the west, with the exception of a limited area of greater than 0.5 R-scores in the south of the area mapped as Kakontwe limestone already noted to have high Ti-Cr-V-Ni-Ga-Co R-scores and low Mn-Fe_2O_3 R-scores.

From a consideration of minor element values in different lithologies and the relationship of Co-Ni-Cr association extracted from the provincial drainage data with basic rocks, an association of Ni-Cr-Co would indicate the presence of basic rocks. The inclusion and dominance of copper in the association, however, suggests the possible association of copper mineralisation with basic rock occurrence. Prior to this interpretation no basic rocks were known in this area of Kadola. Subsequent drilling by Roan Selection Trust Technical Services, independent of this study, has now proved that there is a unit of talcose schist with some amphibolite emplaced as a more or less continuous 100 foot thick unit between two Muva quartzite units. In addition, copper mineralisation was noted to occur primarily in the quartzites in the same drill core. These results will be discussed more fully in the next section on the relation of the minor element associations of the stream sediments to those of the rock and soil data as indicated by factor analysis.

(v) Fe_2O_3-Co-Ni-V-Ga association

The Fe_2O_3-Co-Ni-V-Ga association has relatively high Fe_2O_3 and Co loadings of 0.8 and 0.6 respectively and low Ni, V, Ga loadings of 0.3, and accounts for some 18% of data correlation.

The elements in this factor are only associated together in the five factor model. Co-V-Ni-Ga separate from Fe_2O_3 in the six factor model to form an association including chromium (Table 21). This early separation of the elements in this association suggests that there are perhaps more than one feature controlling their distribution. The element variations with R-score level also indicate a relatively poor correlation (Table 23(e)). Cobalt, nickel, gallium and vanadium show no significant variation between the R-score classes 2.0 to 0.5, in which most of the ferric iron variation takes place, in fact they decrease in value with increasing R-scores and ferric iron content.

Samples with high Fe_2O_3-Co-Ni-V-Ga association R-scores do not appear to have any consistent correlation with any particular rock unit or secondary environmental feature (Fig. 42). No feature can, therefore, be suggested as being reflected by this association.

6.2.4 Implications of the factor associations

In the foregoing section the distribution of the sample R-scores of each factor association were described and related to the various features to which their R-score patterns corresponded. It appeared from this interpretation that the Ti-V-Cr-Ni-Ga-Co, Pb-Ga, Cu-Ni-Cr-Co associations could be related to various lithologic units, that the Mn-Fe_2O_3 association could be related to secondary environmental features and carbonate rocks, whilst the Fe_2O_3-Co-Ni-V-Ga association could not be related to any known features. Assuming these relationships to be correct there are some patterns of high and low R-score values which do not correspond to the mapped lithologic units, and must, therefore, be considered anomalous in the general sense not in the geochemical exploration meaning of the word. These

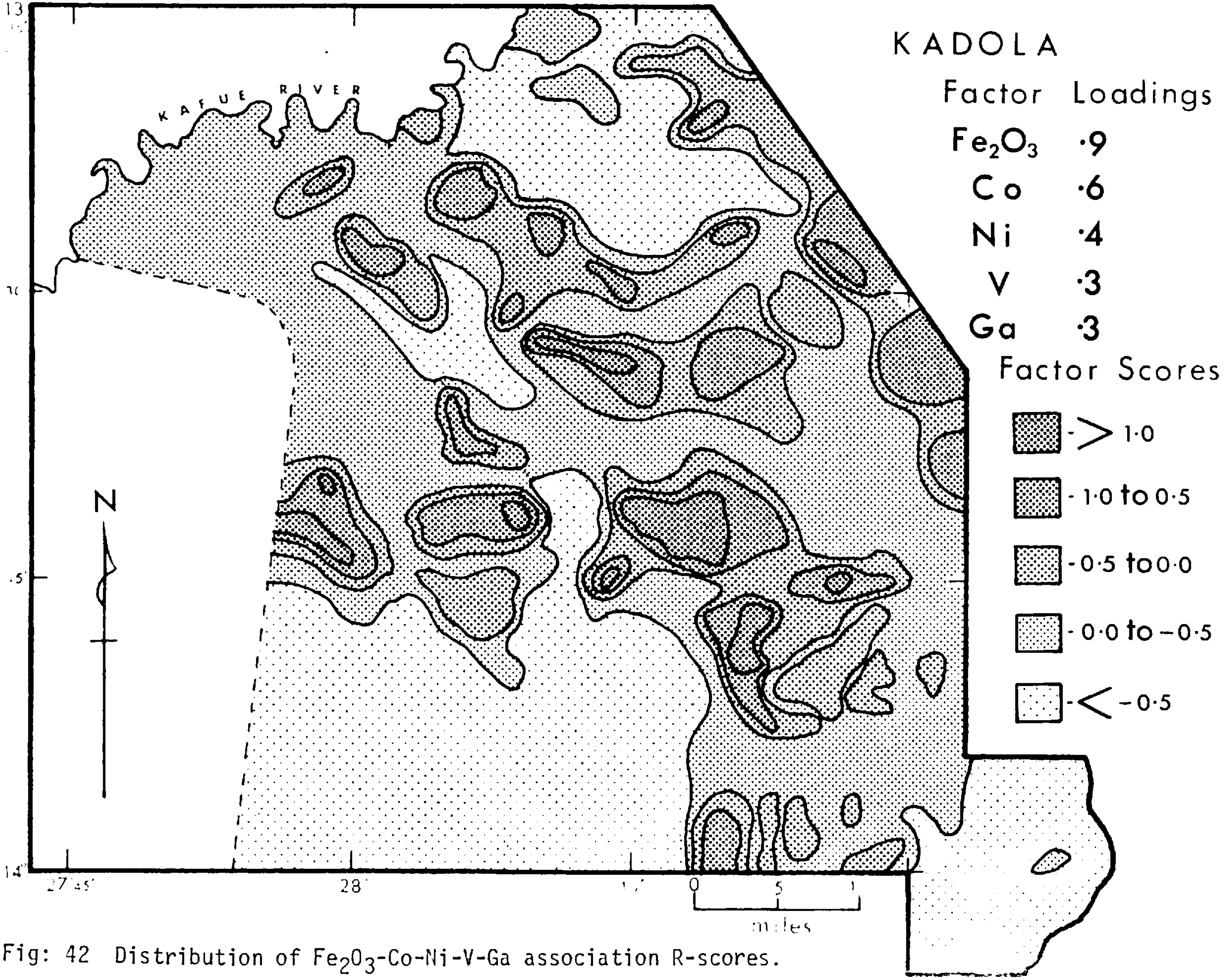

Fig: 42 Distribution of Fe_2O_3-Co-Ni-V-Ga association R-scores.

R-Scores

Element	Loading		2.0	1.0	0.5	0.0	-0.5	-1.0
Fe_2O_3	.8	11.4	4.2	2.3	1.7	1.4	1.0	.8
Co	.6	60	75	65	30	13	8	5
Ni	.3	100	140	110	65	50	30	24
V	.3	65	170	110	60	55	30	15
Ga	.3	14	25	18	11	9	4	3
Cr	.1	60	80	55	40	35	13	11
Mn	.1	440	290	180	110	80	35	80
Cu	-.02	28	45	35	22	22	13	18
Pb	-.04	6	10	8	6	8	4	4
Ti	-.1	4000	6700	5600	3300	3600	1700	2400
No. of samples		12	18	20	24	21	22	25

(all units in ppm except Fe_2O_3 which is a %)

Table 23(e): Fe_2O_3-Co-Ni-V-Ga association discrepancies may be due:

(a) to incorrect geologic mapping as a result of poor exposure,

(b) to geochemical facies change within a geologic unit,

(c) to lack of adequate sample density to define a geologic unit,

(d) to minor element values reflecting features which are not represented by a factor association such as mineralisation. This last point is particularly important in the interpretation of R-scores, because the relatively simple method of calculating R-scores does not take into account the proportions between the elements in a sample as they are indicated by the element loadings in a factor association. For example, a sample with only anomalously high copper content derived from mineralisation would have a high Cu-Ni-Cr-Co R-score value, which would lead to the interpretation that it was derived from basic rocks.

In order to establish with more certainty the causes of the factor associations derived from the minor element content of the drainage sediment samples, rock, soil and additional drainage samples were taken. The areas selected for this sampling were chosen on the basis of:

(a) areas with high R-scores for a particular association, corresponding to the geological or secondary environmental feature to which the association has been related,

(b) anomalous areas; that is, areas of high R-scores which do not correspond to the features to which the association has been related, and

(c) areas of low R-scores for each association were also sampled for the purpose of contrast.

Drainages were resampled in more detail over these selected areas in order to check the results of the original drainage samples.

The soil and rock sample collection was carried out as described in sections 4.2.3 and 4.2.4. Due to the very few outcrops only 114 rock samples were collected and these included many samples of very leached quartzite, and massive carbonate in the form of coarse grained marble. Acid crystalline rocks outcropped occasionally and only rather weathered specimens could be collected. Schistose units outcropped less frequently still and most of the schist rock samples came from exploration pits. No basic rock outcropped and all basic rock samples were taken from drill core. The sample preparation was carried out as described in sections 4.3 and 4.4.

6.2.5 Relationship of minor-element associations in rocks and soils to those in drainage sediments

The rock, soil and replicate drainage sediment data has been factored using 10 elements. These 10 elements included zinc but omitted ferric iron, in contrast to the original drainage sediment data which was factored using ferric iron but not zinc. Initially, zinc was included as a variable with the original drainage sediment data; however, this only resulted in the extraction of a zinc factor with no associated elements and was of little interpretative value. This was probably due to more than 50% of the samples having zinc values below the detection limit of 50 ppm, resulting in statistically poor correlation coefficients. From the experience with provincial data (section 5.3.2) the inclusion of zinc and the omission of ferric iron analyses has not led to significant changes in the main associations extracted by factor analysis.

Despite the different variables used in the factor analytical solutions, the extreme weathered character of the rocks, soils and drainage sediments, the very different sampling distributions and the fewer number of samples, the main factor associations extracted from the different sample media are comparable (Table 24). The differences and similarities in the associations and the R-score patterns and anomalies will be discussed in the following subsections.

(i) Ti-V-Ga association

An association dominated by titanium but with high vanadium and gallium loadings is extracted from the rock data (Table 24). Argillaceous and schistose rock samples have the highest mean Ti, V and Ga content with titanium values 2-3 fold, vanadium 2-4 fold and gallium 2 fold higher than most other units (Table 25). Similarly the mean R-scores of the Ti-V-Ga association of argillaceous and schistose rock samples are over twice the mean R-scores of other rock types (Table 26). There is little doubt, therefore, that Ti-V-Ga association is reflecting argillaceous and schistose units.

The associations with titanium as the dominantly loaded element which are extracted from the sets of drainage sediment data and the V-Ga-Ni association extracted from the soil data appear to be equivalent to the Ti-V-Ga association extracted from the rock data.

The reasons for the minor differences in the constituent elements of these equivalent associations are a combination of: (a) the redistribution of the elements in the secondary environment, (b) the difference of sample distribution from the various controlling bedrock types, and (c) the inadequate detection limits at the upper and lower limits of the titanium and chromium ranges in value respectively.

Sample Medium	Rocks			Soils			Drainage Sediment					
							(initial samples)			(replicate samples)		
	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for
Factor associations	Ti V Ga	.9 .9 .6	20%	V Ga Ni	.9 .5 .3	13%	Ti V,Cr Ni Ga Co	.9 .6 .5 .4 .3	27%	Ti Cr V	.9 .4 .4	13%
	Pb Ga	.9 .4	12%	Pb Ga	.9 .7	15%	Pb Ga	.9 .5	13%	Pb Ga	.9 .4	13%
	Mn Co Zn	.9 .5 .3	14%	Mn Ti	.8 .8	15%	Mn Fe_2O_3	.9 .3	11%	Mn Zn	1.0 .4	12%
	Ni Cr Zn Cu Co	1.0 .9 .7 .7 .6	33%	Cr Cu Ga	.9 .6 .3	14%	Cu Ni Cr Co	.9 .4 .4 .3	16%	Ni Cr Zn Cu Co	1.0 .7 .6 .5 .4	24%
	Cu Ga	.6 -.5	6%	Co Zn Ni Cu Mn	.8 .8 .7 .6 .3	25%	Fe_2O_3 Co Ni V,Ga	.8 .6 .3 .3	18%	V Ga Co Cu	.8 .7 .5 .5	20%
Total % data accounted for by factor models			85%			82%			85%			82%
No. of samples	114			376			481			199		

Table 24: Element associations in different sample media from Kadola

Element	Geologic unit	Basement Complex					Katangan System		
		Muva Basic unit	Northern acid crystalline unit	Southern acid crystalline unit	Muva Quartzite	Muva and Lufuba Schist	Lower Roan Quartzite	Upper Roan and Mwashia Schists	Upper Roan and Kakontwe Carbonate
Co	Mean*	170	17	30	16	29	18	20	35
	Range**	120-200	11-28	6-13	10-23	22-40	9-40	12-30	25-45
Cr		400	55	40	50	85	40	75	40
		210-800	40-90	no range	40-70	70-136	no range	55-95	no range
Cu		490	10	20	23	40	11	24	11
		170-800	no range	12-35	10-35	16-70	8-14	12-50	5-23
Ga		12	14	15	8	23	9	25	8
		10-16	10-20	10-23	no range	13-35	8-10	16-40	no range
Mn		180	35	130	30	85	17	40	75
		80-500	6-170	60-200	3-110	13-220	6-45	10-180	23-260
Ni		500	10	17	18	35	14	24	15
		400-700	no range	12-24	11-28	19-40	9-19	12-45	10-23
Pb		2	5	4	2	4	2	2	1
		1-4	no range	4-5	1-4	no range	1-4	1-4	1-4
Ti		5000	2500	5500	1500	10,500	9000	12,000	300
		4000-7000	1000-5500	5000-6000	900-4000	8000-16,000	5000-16,500	7000-20,000	1500-6000
V		27	10	23	9	60	35	200	9
		10-70	2-40	6-85	3-16	50-100	12-85	90-440	5-16
Zn		75	11	27	11	35	13	23	18
		70-90	9-14	15-50	9-13	12-45	9-17	16-30	14-23
No. of samples		6	3	4	11	9	16	4	41

*Geometric means **Single standard deviation ranges All units in ppm

Table 25: Mean element content and single standard deviation ranges of rock samples from different geologic units in Kadola.

Geologic unit / Factor associations	Basement Complex					Katangan System		
	Muva Basic unit	Northern acid crystalline unit	Southern acid crystalline unit	Muva quartzite	Muva and Lufuba schist	Lower Roan quartzite	Upper Roan and Mwashia schists	Upper Roan and Kakontwe carbonate
Ti-V-Ga	+.3*	-.4	+.3	-.8	+1.3	+.6	+1.9	-.5
Pb-Ga	+.1	+1.3	+1.1	+.3	+1.2	-.2	.0	-.7
Mn-Co-Zn	+.8	-.5	+.6	-.5	.0	-.6	-.3	+.4
Ni-Zn-Cr-Co-Cu	+2.7	-.6	-.2	-.4	+.6	-.7	.2	-.4
Cu-Ga (-)	+1.0	-.5	-.4	+.5	-.5	+.4	-.7	-.1
No. of samples	6	3	4	11	9	16	4	41

*Arithmetic means

Table 26: Mean association R-scores of rock samples from different geologic units in Kadola area.

The omission of titanium in the association extracted from the soil data is due firstly to the strong correlation of titanium with manganese resulting from the concentration of ilmenite in soils over carbonate rocks. (This feature will be described further in the discussion of anomalous Ti-V-Cr-Ni-Ga-Cu R-score patterns.) Secondly, it is also due to there being 30% of the soil samples having titanium values greater than the 20,000 ppm detection limit. This could have led to the low correlation coefficients with elements which correlate with titanium in the upper end of its range of values. Chromium is probably omitted from the rock and soil associations for much the same reasons. Sixty-nine per cent of the rock samples and 43% of the soil samples have chromium contents below the 50 ppm detection limit compared with 23% of the replicate drainage sediment samples. The mean chromium content in argillaceous and schistose rocks are between 50-100 ppm. This suggests that the correlation between chromium and the other elements related to these rocks is mainly within the 50-100 ppm range of values. The lack of chromium values in the 0-50 ppm range, however, will result in a correlation coefficient too low for chromium to have a significant loading with the other elements in argillaceous and schistose rocks, because of an insufficient, sympathetic range of values.

Soil samples overlying schists or argillaceous rock units have the highest R-scores in the V-Ga-Ni association indicating its equivalence to the Ti-V-Ga association extracted from the rock data (Table 27).

The difference between the titanium associations extracted from the initial and replicate drainage sample data is probably due to the different proportion of samples over different rock types.

Under-lying geologic units / Factor Associations	Basement Complex				Katangan System		
	Muva Basic unit	Acid crystalline unit in north	Acid crystalline unit in south	Muva and Lufuba schists	Lower Roan Quartzite	Upper Roan and Mwashia schists	Upper Roan and Kakontwe Carbonate
V-Ga-Ni	-.1*	.1	-1.8	.5	-.4	.6	.5
Pb-Ga	-.1	1.5	3.1	.6	-.4	-.5	-.2
Mn-Ti	-.2	.1	-1.0	.2	-.6	.1	.5
Cr-Cu-Ga	1.7	0	-1.0	1.1	-.7	-.4	.1
Co-Zn-Ni-Cu-Mn	-.1	-.3	-.5	-.4	-.9	.2	.8
No. of samples	30	28	11	22	38	40	115

*Arithmetic mean R-scores

Table 27: Mean association R-scores of soil samples overlying different geologic units in Kadola area.

A considerably greater proportion of replicate drainage samples were taken from dambos draining basic rocks around Jack's Mine and the Muva basic rocks than were included in the initial drainage samples. This has resulted in a stronger mafic element factor association extracted from the replicate drainage samples compared to the equivalent association from the initial drainage sample data.

Field work was carried out over two areas where high Ti-V-Cr-Ni-Ga-Co association R-scores did not correspond to argillaceous rocks. Both areas are over the main central area which is mapped as Kakontwe limestone (Fig. 43). One area extends over the eastern central nose of the Kakontwe limestone from the main pattern over the Upper Roan shale and dolomite, and Mwashia shale unit. The second area occurs over the southern part of the central area mapped as Kakontwe limestone. These patterns were thought to be anomalous either because of incorrect mapping or else facies change within a rock type.

Despite the lack of outcrop, traverses over the former area indicated that the mapped geologic boundaries are correct. As mentioned in section 3.2, soil and vegetation is different over the various lithologies, and the soil changed sharply from a dark red or brown sandy clay over the area mapped as Kakontwe limestone to light rusty yellow clayey sand over the area mapped as Mwashia schist. In addition, the 'peppercorn' vegetation pattern seen on aerial photographs, which characteristically occur over schistose units, do not extend over the area mapped as Kakontwe limestone. Finally, marble outcrops extensively in the dambos, where the samples with the anomalously high Ti-V-Cr-Ni-Ga-Co R-scores were taken. The

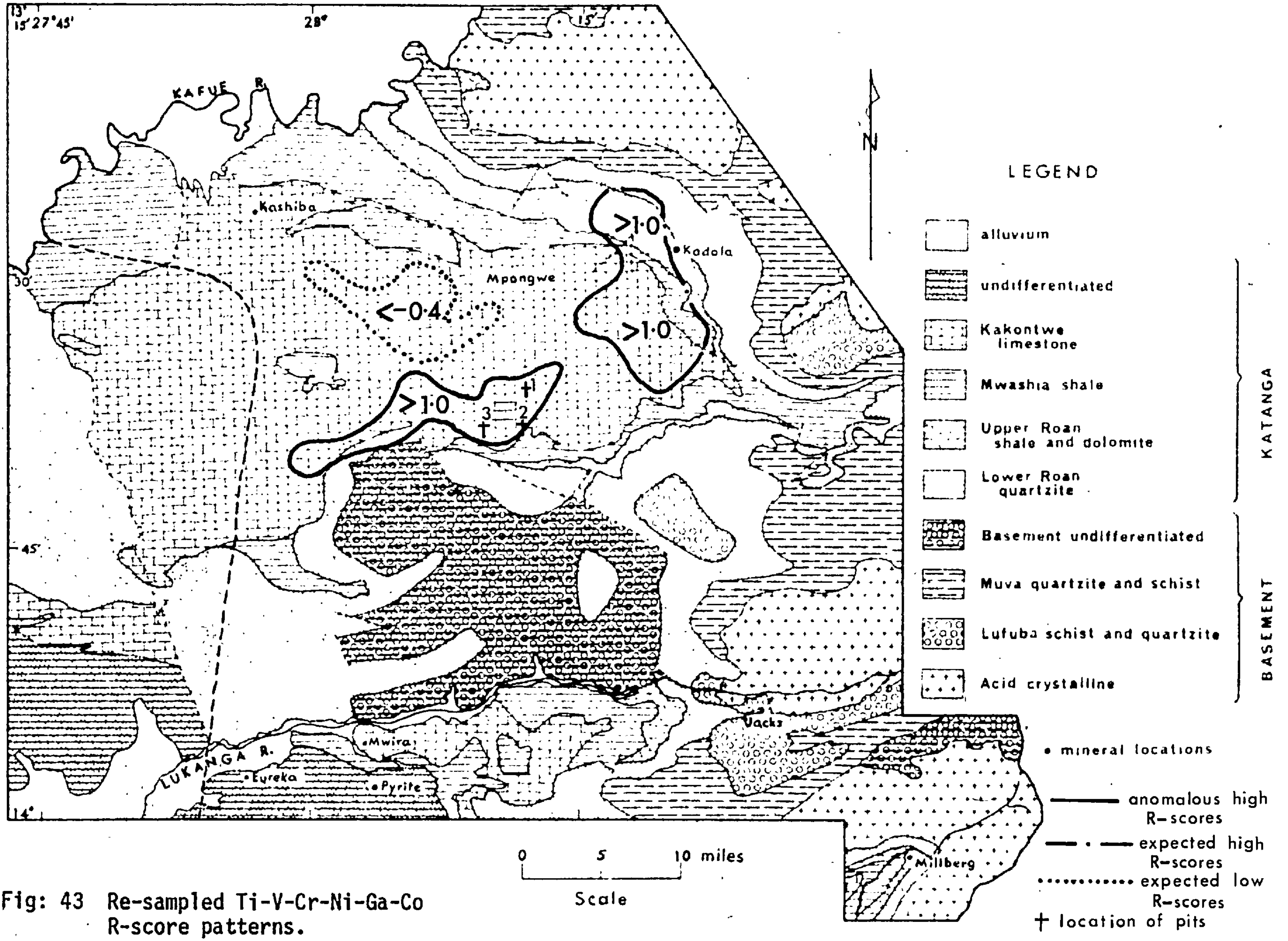

Fig: 43 Re-sampled Ti-V-Cr-Ni-Ga-Co R-score patterns.

possibility that the high Ti-V-Cr-Ni-Ga-Co association R-scores are due to incorrect mapping in this area can, therefore, be discounted.

A black metallic mineral was noted to be concentrated on the surface of the soils in this area. This has been identified as ilmenite on the basis of an X-ray powder photograph and a high titanium content checked by X-ray fluorescence at the Geological Survey of Zambia by G. Matheson. This mineral occurs as an accessory in some facies of the marble, and because of its resistate nature is concentrated in the overlying soils and drainage sediments on the weathering and solution of the marble. By classifying the marble samples on the basis of colour it was possible to show that the lighter grey and white marbles had a mean Ti-V-Ga R-score of -0.8 whereas the darker grey and sometimes more argillaceous marbles had a mean Ti-V-Ga R-score of -0.2.

In conclusion, therefore, the anomalous Ti-V-Cr-Ni-Ga-Co association R-score pattern has indicated a mineralogical change in the accessory minerals of the carbonate bedrock. This change, however, is only evident because ilmenite is a resistate mineral which is concentrated in the soils relative to the underlying bedrock. This feature must, therefore, be regarded as much of secondary environmental as primary origin.

No outcrop was found on the traverses over the second area of anomalous Ti-V-Cr-Ni-Ga-Co R-scores although carbonate rock did outcrop to the north of the pattern. The soil and vegetation types changed dramatically over the anomalous area to a 'peppercorn' pattern which characteristically develops over schistose rock types.

Three pits were dug in order to get definite proof of the underlying bedrock type (Fig. 43). Two of these pits (pits 1 and 2) reached a bedrock of schistose or phyllitic rock. The third pit reached the water table at 10 feet in thick laterite (see appendix 2 for description of pits). All three pits encountered thick laterite which is another characteristic development of soils over schistose rock units.

The above evidence shows that the Ti-V-Cr-Ni-Ga-Co R-score pattern has in this case correctly indicated a discrepancy between the mapped and true bedrock type. Older geological maps, made by Concession Geologists in the 1930's, in fact show this area as a shale unit overlying the Kakontwe limestone (Wainwright, N., pers. comm.). This unit was omitted on the later geological maps.

(ii) Pb-Ga association

The Pb-Ga association extracted from the original drainage sediment data was correlated with the acid crystalline rock units on the basis of the correspondence of the high Pb-Ga association R-score patterns with these rock units. Mean lead and gallium values in dambo and stream sediments draining the acidic crystalline units in the north are about twice those draining other rock units and about half to a third those in sediments draining the southern acid crystalline rocks (Table 20).

Rock and soil sampling was carried out over both occurrences of acid crystalline rock. Outcrop was very poor and only seven rather weathered and leached granitic rock samples were collected. The mean lead content of these rock samples are twice the value of other rock types with the exception of the Muva and Lufuba schists, although all the rock samples have extremely low lead content (Table 25). This low lead content in the rock samples is probably due to the leached condition of the rock samples. Despite this small variation in the lead data, a Pb-Ga association is extracted from the rock data. The same association is also extracted from the soil and replicate drainage samples. The mean Pb-Ga association R-scores of the acid crystalline rocks and soils overlying the acid crystalline rocks are distinctly higher than samples from other rock types with the exception of the Muva and Lufuba schists (Tables 26, 27). The soil samples like the drainage sediment samples have a considerably higher Pb-Ga R-score over the southern compared to the northern acid crystalline units. This variation of lead content is not detected in the rock samples probably because of the greater extent of leaching which the more weathered rock samples from the south have undergone and the inadequate number of rock samples for gaining an accurate knowledge of the overall geochemistry of each unit.

Drainage sediment samples with high Pb-Ga association R-scores which do not correspond to underlying granitic bedrock occurs over an area mapped as Kakontwe limestone south east of Kashiba (Fig. 44). High Mn-Fe_2O_3 association R-scores suggest that the area is underlain by a carbonate unit. Traverses over the area confirmed, from extensive outcrops, that the geologic map was correct. Rock and detailed soil and drainage sampling traverses were carried out across the area. None of these samples had higher lead contents than other samples from a similar environment. A small fluorite veinlet was noted but a sample of this did not carry any lead values. The relatively high lead values of the original drainage samples could not be reproduced from the detailed drainage sediment samples. One of the

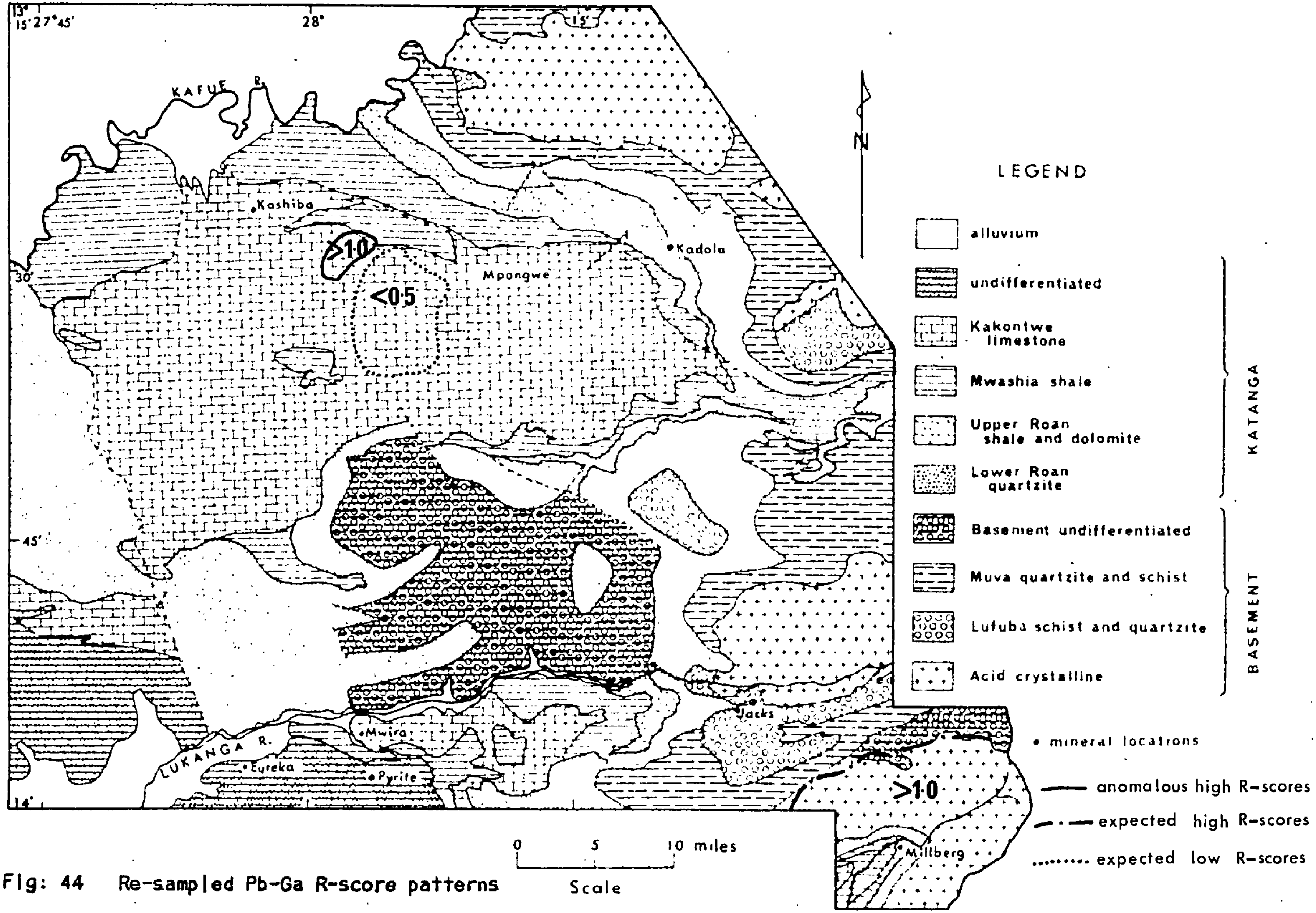

Fig: 44 Re-sampled Pb-Ga R-score patterns original drainage samples with the relatively high lead value of 20 ppm was reanalysed and gave a value of 16 ppm. This indicates that the original analysis was probably correct. It appears, therefore, that either the original sampling was incorrect or the sample has been contaminated.

Around the Millberg lead, zinc showing in the south east of the field area, there were not drainage sediment samples available from the original survey. Rocks, soils and some drainage sediment samples were taken in the area during follow-up work in order to establish whether this mineralisation would be picked up as an anomaly in a regional geochemical survey.

The majority of the rock, soil and drinage samples taken from this area tend to have higher lead, zinc values and Pb-Ga association R-scores than would be expected from Katangan rocks. The two quartzites and two arkosic conglomerates from the Lower Roan had detectable lead values compared with undetected lead in the majority of the Katangan samples elsewhere, which give rise to comparatively high mean Pb-Ga R-score of 0.9. Zinc values for these rock samples appear to be slightly enhanced since 3 out of the 4 samples tend to be greater than 10 ppm whereas only 3 out of 12 Lower Roan samples elsewhere have zinc values greater than 10 ppm. A sample of metamorphosed carbonate rock from the Upper Roan which was composed mainly of actinolite gave values of 100 ppm lead and 65 ppm zinc which are anomalously high compared with carbonate rock samples. The 14 soil samples taken in the area have a mean Pb-Ga association R-score of 0.9 which is three times higher than mean values for soils overlying similar units elsewhere (Table 27). Out of 9 drainage samples taken in the area, 8 samples have Pb-Ga association R-scores over

0.4 and 6 of these are greater than 2.0. These 9 samples are taken from an area of some 8 square miles. Although it would be unlikely for a Pb-Zn mineralisation association to be extracted by R-mode factor analysis from regional geochemical survey data, a sampling density of one sample every 2 square miles would not have failed to have some high Pb-Ga R-scores. These high Pb-Ga R-scores could then be considered anomalous and indicating that the area requires more detailed sampling if, either the geology, or the R-score distributions of other associations, indicate that bedrocks other than granite are present.

In conclusion, therefore, the above evidence shows the Pb-Ga association extracted from the geochemical data from the Kadola area is a reflection of granitic or acid crystalline rock units, and that samples with high Pb-Ga R-scores are likely to be derived from these rock units. Where geological, or other evidence such as high R-scores in different associations, suggests that rock units other than granite are present, these features might indicate the presence of lead mineralisation.

(iii) Manganese and associated elements

The Mn-Fe_2O_3 association extracted from the original drainage sediment sample data was related on the basis of the high R-score patterns to the carbonate rocks and the secondary environment as it is controlled either by this rock type, or basic and ultrabasic rocks.

An association with manganese as the main element is extracted from the data from all the sample media, but the associated elements vary somewhat (Table 24). These associated elements, with the exception of titanium in the Mn-Ti association extracted from the soil data, tend to have relatively low loadings, however, suggesting only a fairly weak correlation with manganese.

A Mn-Co-Zn association is extracted from the rock sample data. The reason for this cobalt and zinc association with manganese is a result of the general sympathetic correspondence of cobalt and zinc with manganese in the rock samples (Table 25). Basic and carbonate rocks have high Mn-Co-Zn R-scores (Table 26). In addition the southern acid crystalline rocks have a relatively high Mn-Co-Zn R-score. This is because of the fairly high Mn, Co and Zn values in the few samples taken from this unit, and is probably a reflection of an acid igneous rock of more intermediate composition than the northern acid crystalline.

The omission of cobalt from the manganese associations extracted from the drainage sediment data is surprising considering that it has been shown by Horsnail (1968) that manganese hydroxides precipitated in drainages tend to absorb cobalt ions. The stream beds in Wales are, however, very different from the dambos in Zambia. In Wales the manganese hydroxides are typically precipitated in continually wet stream beds and, therefore, have the maximum opportunity of coming into contact with cobalt ions in solution. In dambos, on the other hand, the manganese hydroxides are precipitated on the surface of the dambo soil profile which are dry for much of the year and, therefore, have only a limited opportunity of coming into contact with ions in solution. The manganese association extracted from the soil data includes titanium with a high loading. This strong correlation of manganese with titanium probably results firstly from the concentration of resistate minerals in the upper part of the soil profile and secondly the inappropriate titanium analytical results in view of the higher values of titanium in the soils. These points are elaborated below.

(a) High titanium values in the soils have already been shown to be due to the concentration of ilmenite in the upper soil horizons resulting from the eluviation of the finer particles. Manganese oxide pellets or concretions once formed, are insoluble and in the soil profile will behave in much the same way as a primary residual mineral. Since ilmenite occurs in carbonate rocks and manganese oxide in soils over carbonate rocks it is reasonable to expect a Mn-Ti association from the soil sample data. R-scores in this association are highest in soil samples overlying carbonate rocks (Table 26).

(b) The strength of this correlation and association might also have been enhanced, because 30% of the soil samples have titanium values greater than the Upper detection limit of 20,000 ppm.

Two areas of anomalous Mn-Fe_2O_3 R-scores were resampled. One area of negative or low Mn-Fe_2O_3 R-scores representing low Mn and Fe_2O_3 contents over an area mapped as Kakontwe limestone, and a second area of high Mn-Fe_2O_3 R-scores over Muva quartzites and schists (Figure 45).

The former area lying on the southern side of the main Kakontwe limestone has already been shown (section 6.2.5(i)) to be underlain by schistose rather than carbonate rocks. In so far as high Mn-Fe_2O_3 R-scores are associated with underlying carbonate rocks, the low Mn-Fe_2O_3 R-scores can be used to indicate their absence.

The latter area lying along the eastern edge of the field area will be shown in the following section (6.2.5(iv)) to be underlain in part by basic rock units. In so far as it has been shown that basic rocks have high Mn-Co-Zn R-scores (Table 26), the high Mn-Fe_2O_3 R-scores will indicate, when combined with high R-scores of mafic element associations underlying basic rock units.

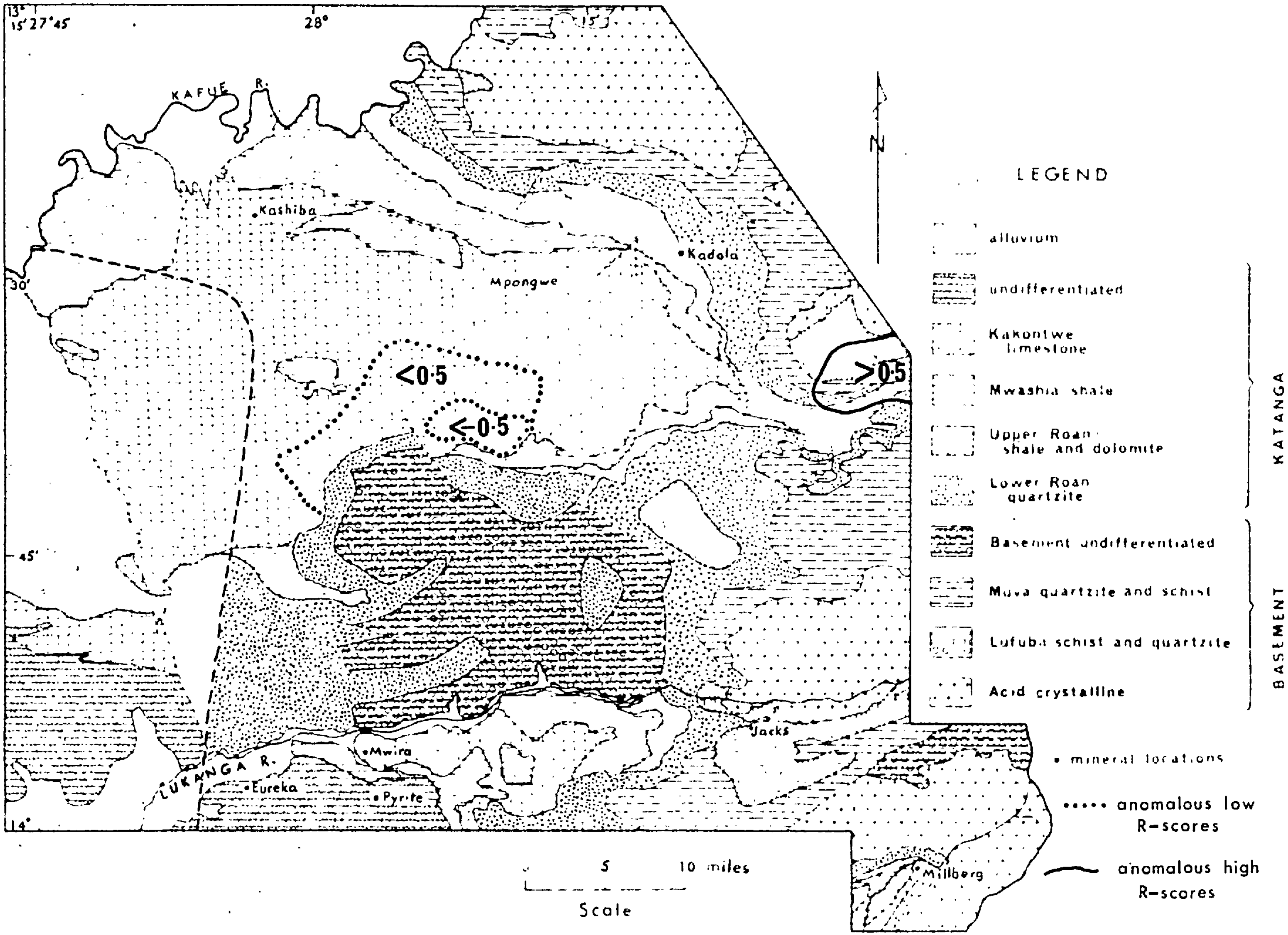

Fig: 45 Re-sampled Mn-Fe_2O_3 R-score patterns.

Secondary environmental features, except in so far as they are controlled by carbonate and basic rocks, do not appear to influence the distribution of manganese and associated elements to the same extent as the provincial data. Kadola is not a large enough area to experience any differences in rainfall in different parts. The dambo type of drainage sediments are also similar throughout Kadola except when the pH is raised by underlying carbonate or basic rocks. In addition to the higher manganese in both basic and carbonate rocks compared with other rock types (Table 25), there will be a considerable accumulation of these elements in the drainages because of their restricted mobility in the higher pH conditions.

In conclusion, therefore, the Mn-Fe_2O_3 association extracted from the drainage sediment data is a reflection of underlying carbonate or basic rocks and the secondary environmental conditions to which these lithologies give rise. Drainage sediment samples with relatively high Mn-Fe_2O_3 R-scores can be taken as an indication that either of these lithologies are in the upstream catchment area from the sample.

(iv) Ni-Cr-Co association

The occurrence of basic rocks with associated copper mineralisation in the area of Muva quartzites and schists was suggested on the basis of the high Cu-Ni-Cr-Co association R-scores in the north east of Kadola. Outcrop was very poor in the area and only a few quartzite ridges occurred above the thick soil cover. As already mentioned (section 6.2.3(iv)), diamond drilling in the area, independent of this study, proved the existence of basic rock units in association with the Muva quartzites. The drill holes were located on the basis of drainage and soil anomalies from geochemical surveys carried out by R.S.T.T.S. (Fig. 46 for location of drill holes.) A 100 foot thick unit of talc or amphibolite schist between two quartzite units was shown to occur (appendix no. 3 for logs of drill holes). Copper mineralisation, mostly chalcopyrite, commonly occurred in the quartzite, particularly when it was adjacent to the basic schist. Analyses from five basic schist samples from the drill core were included with the rock sample data for factor analysis. The sixth 'basic' rock sample was a serpentinite from Jack's Mine.

A Ni-Zn-Cr-Co-Cu association is extracted from the rock sample data (Table 24). Rock samples with highest mean R-scores in this factor are the basic rocks (Table 26). An identical association with minor variations in the loadings is extracted from the replicate drainage sediment data. These factors are similar to the equivalent association extracted from the original drainage sediment sample data except that copper is no longer the dominantly loaded element. The reason for this difference between factors from the original drainage sediment and the rock data is because the highest copper values in the rock samples were not in the basic rocks, but in the associated mineralised quartzites, whereas the drainage samples combine the elements from these separate sources. This is reflected in the Cu-Ga(-) association (N.B. gallium is negatively loaded with respect to copper) extracted from the rock sample data, and Cu-Ni-Cr-Co association extracted from the drainage sediment data. The negative loading of gallium is a reflection of the low aluminium content in quartzites compared to other rock types, since gallium is governed by a diadochy with aluminium (Rankama and Sahama, 1949). The dominant copper loading in the Cu-Ni-Cr-Co association from the drainage data appears, therefore, to be a good indication of copper mineralisation in the same catchment area as basic rocks. The R-scores of this association, however, will not be very helpful at indicating which samples drain mineralisation since they will tend to be high whether they drain basic rock mineralisation or both. Once the presence of basic rocks has been established by the characteristic Ni-Cr-Co association a simple Cu:Ni ratio would probably be the best technique for differentiating samples draining copper mineralisation from those draining basic rocks only.

The difference between the associations extracted from the replicate and original drainage sample data is probably because few, if any, of the replicate drainage samples were from drainages with high copper in the stream sediment. Copper, therefore, has not been chosen as the dominantly loaded element in the association.

Cr-Cu-Ga appears to be the equivalent association extracted from the soil data. Soil samples over Muva quartzites and schists where underlying basic rocks are suspected have the highest mean R-score in this association (Table 27). The lack of the more mobile cobalt, nickel and zinc in the association suggests they have been leached. The soil samples with high mean Cr-Cu-Ga R-scores have surprisingly low mean Co-Zn-Ni-Cu-Mn R-scores considering that most of these elements tend to be high in basic rocks. This is a further indication that these elements tend to be leached from the soils relative to chromium, copper and gallium.

There is an area of apparently anomalous high Cu-Ni-Cr-Co association R-scores over the northern acid crystalline unit (Fig. 46). Traverses over the area revealed only one outcrop of quartzite ridge trending in a NW-SE direction. This quartzite occurs north of the southern boundary of acid crystalline marked on the map (Fig. 46).

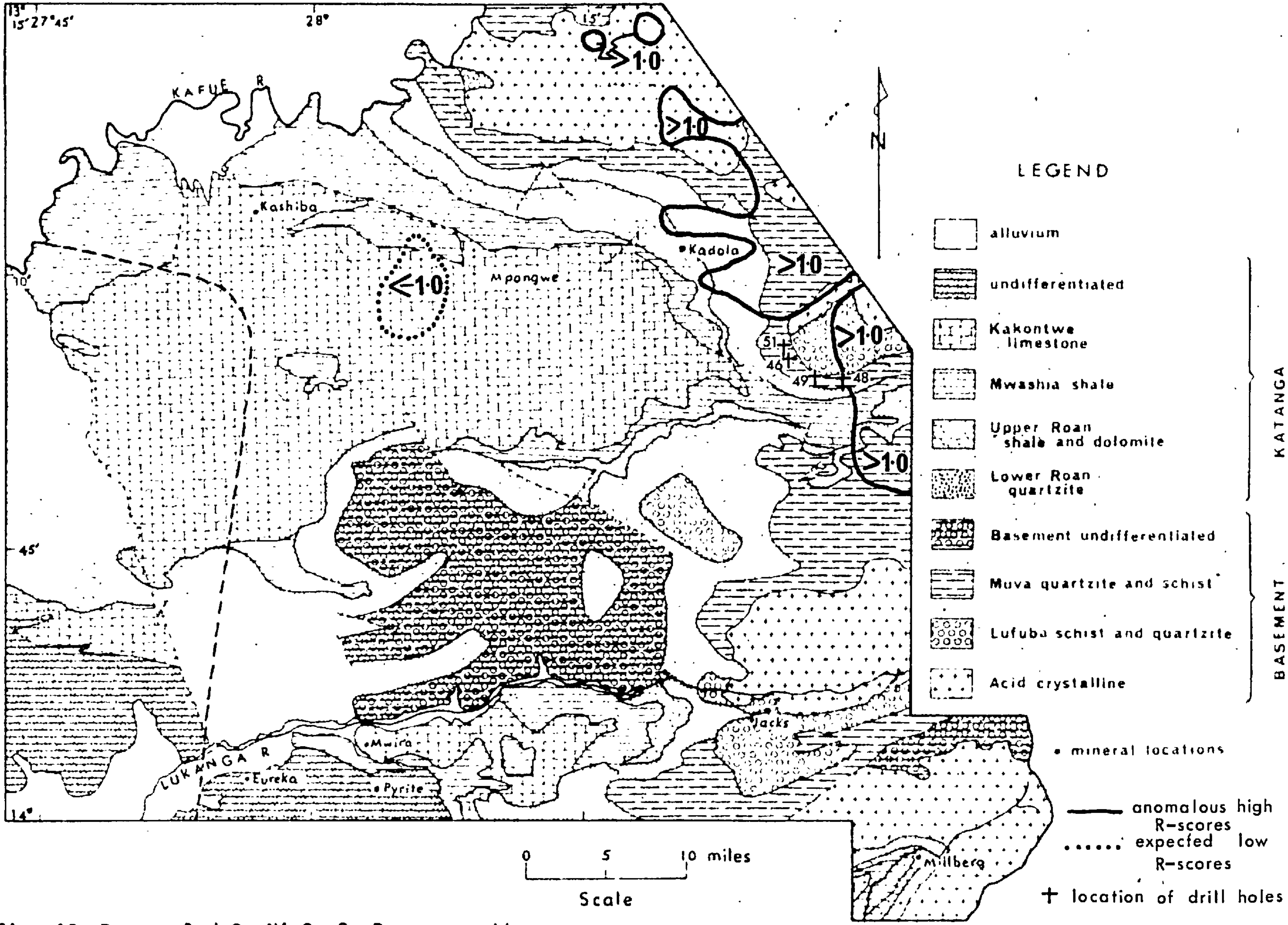

Fig: 46 Re-sampled Cu-Ni-Cr-Co R-score patterns.

The eleven soil samples taken from the anomalous area have a mean Cr-Cu-Ga R-score of 0.3 which is considerably higher than soils over most other rock types, and in particular the -1.0 mean R-score of soils over the southern acid crystalline units. The replicate drainage samples have a similarly high Ni-Cr-Zn-Cu-Co R-scores over the anomalous area. Nine samples within the anomalous area have mean R-scores of 0.7 compared to -0.3 of eight samples draining the northern acid crystalline unit outside the anomalous area. These results show that the original drainage sample results were correct. Coupled with the outcrop of quartzite, which is known to be associated with basic rocks to the south east, they suggest that either the boundary with the acid crystalline unit is located too far south, or that quartzite and associated basic rocks are incorporated in the acid crystalline unit.

In conclusion, therefore, the Cu-Ni-Cr-Co association extracted from the original drainage sediment data reflects basic rocks, and indicated their presence in association with the Muva quartzite and schists where they were not previously known to occur. The dominant copper loading in the association and the variation of element values with R-score value mentioned in section 6.2.2(iv), suggested the copper mineralisation found in close association with the basic rocks.

(v) Fe_2O_3-Co-Ni-V-Ga association

From the distribution of the R-scores of the Fe_2O_3-Co-Ni-V-Ga association extracted from the original drainage sediment sample data it has not been possible to relate this association to any particular geological or secondary environmental feature. The fifth factor from the rock sample data is a Cu-Ga(-) association. (N.B.

gallium is negatively loaded). Rock samples with high R-scores in this association are the quartzite samples from the drill core which have copper mineralisation (Table 26). This is clearly not an equivalent association. The V-Ga-Co-Cu association extracted from the replicate drainage sediment data does not correspond to either of the above associations. Samples with high R-scores in this association are mostly from dambos draining schist units. The fifth factor extracted from the soil data, Co-Zn-Ni-Cu-Mn, is more similar to the Fe_2O_3-Co-Ni-V-Ga association from the original drainage sediment data but not convincingly so. Soil samples with the highest R-scores in this association overlie carbonate rocks (Table 26).

Clearly it has not been possible to reproduce any association identical to Fe_2O_3-Co-Ni-V-Ga extracted from the original drainage sediment data from the data from the follow-up samples. This is possibly due:- (a) mostly to the lack of iron analyses of the follow-up samples, and (b) to the different sample distribution pattern of the follow-up samples relative to the original drainage samples.

During the course of field work the only feature that appeared as if it might be responsible for an Fe_2O_3-Co-Ni-V-Ga association was outcropping iron laterite. Although iron laterite forms to greater thickness over schistose and argillaceous units it occurs in varying degrees over most rock units and the conditions which would make iron laterite available in the dambo sediment are not controlled by the underlying geology but by secondary environmental features. For example, some dambos have eroded their banks until the laterite formed in the soil profile is exposed and sheet wash will then transport eroded laterite into the drainage channel. The extent to which this will take place and lead to enhanced Fe_2O_3-Co-Ni-V-Ga R-scores in the sediment will depend on the initial presence of laterite in an area where there is adequate relief to expose it, or where it is at a shallow enough depth and where the banks of the dambo or drainage channel are steep enough to allow transport of the eroded laterite to the drainage channel. A second example of iron laterite concentration in the drainage sediment is in some dambos over carbonate rock. The accumulation of oxide pellets in some shallow dambo soils over carbonate rocks has already been noted in discussing the Mn-Fe_2O_3 association (6.2.4(iii)) variation. The Mn-Fe_2O_3 R-scores, however, appear to be high in all types of dambo sediment over carbonate rock whereas the Fe_2O_3-Co-Ni-V-Ga R-scores are only high in certain very dry shallow dambo sediment. For example, on traversing a pattern of high Fe_2O_3-Co-Ni-V-Ga R-scores the original drainage samples were found to have been taken along the edge of the dambo channel where oxides had accumulated over the carbonate rock (Fig. 47). These samples and the replicate drainage samples have a particularly high ferric iron value, of 10% or greater, compared to samples taken from the drainage channel sediment of black wet mud which had much lower ferric iron values of about 1%. The other elements in the association are sympathetically higher with ferric iron.

These features which might give rise to the relative concentration of ferric iron and the associated elements in drainages are likely to occur in a relatively random fashion over the area. Even in the same dambo, samples a few hundred feet apart might give very different results because of the presence or absence of outcropping laterite, or drainage sediment type over carbonate rock. Adequate field evidence has not been collected to show definitely that these are the features controlling the Fe_2O_3-Co-Ni-V-Ga association but the above arguments suggest that they might be.

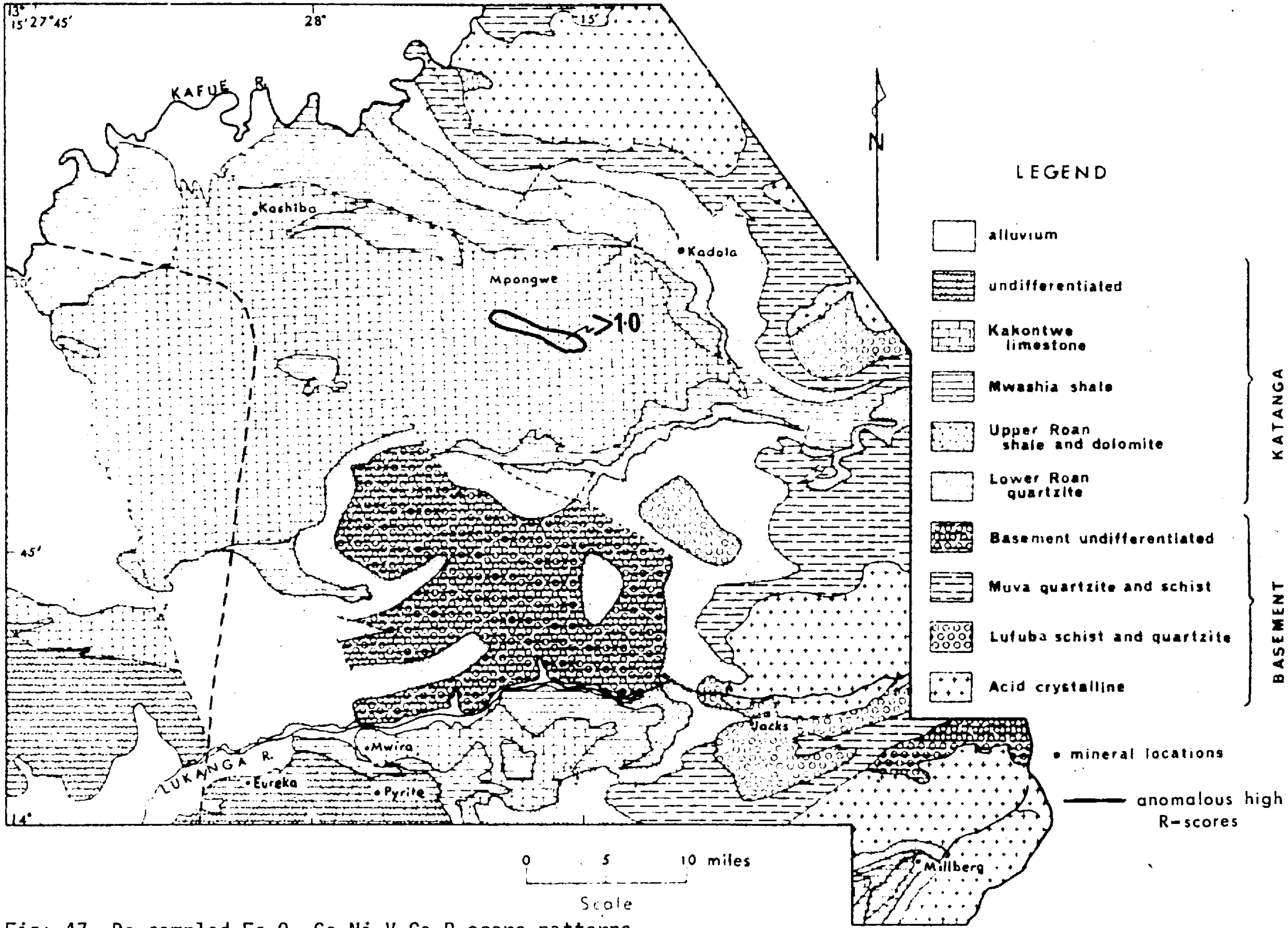

Fig: 47 Re-sampled Fe_2O_3-Co-Ni-V-Ga R-score patterns.

6.3. LUSAKA EAST

6.3.1 Relationship between minor-element content of drainage sediment and geology

All the drainage sediment samples from Lusaka East were analysed for 15 elements. Only 10 of these elements were above the detection limit in a sufficient number of samples to be included as variables in the data for factor analysis. Bismuth, molybdenum, silver, tin and zinc being below the limit of detection in the majority of samples. Maps of the plotted minor-element data revealed certain areas, particularly in the centre and south-east, where the background values of the mafic elements were considerably increased. These areas corresponded in general to known basic rock outcrops. As has been previously stated, it is impossible to identify by visual examination the results of more than two or three elements at a time to show either meaningful relationships with the geology or inter-element correlations.

Mean element content of stream sediments draining the four main lithologic units show that, besides high contents of the mafic element being associated with basic rock units, lead is highest in stream sediments draining granites (Table 28). There is very little apparent variation in element content between streams draining quartzites and micaceous schists. This is probably due to the difficulty of separating stream sediment samples draining only one rock type, firstly because of the close relationship between the schistose and quartzite units, and secondly because of the scale on the geologic map.

Rock Type Element	Amphibolites and Epidosites	Quartzite	Granite and Gneisses	Micaceous Schists
Co GM* Range**	30 16-60	22 9-50	15 7-30	17 9-30
Cr	100 55-170	75 28-200	45 26-85	65 35-120
Cu	23 7-75	10 3-34	6 1-22	8 2-27
Fe_2O_3	9% 4-22	5% 3-9	4% 2-7	5% 3-8
Ga	12 8-19	9 5-17	11 6-20	9 7-14
Mn	1000 500-2000	600 200-2000	400 150-1000	800 600-1000
Ni	30 16-55	23 8-65	15 7-30	17 8-40
Pb	12 9-17	13 8-22	16 10-28	11 7-20
Ti	9500 6000-14000	7000 5000-10000	5500 4000-8500	6500 4500-9500
V	310 130-700	95 45-200	75 35-150	75 45-100
Zn	55 40-80	45 40-55	45 40-50	45 40-50
No. of samples	26	37	262	65

*Geometric mean **Single standard deviation range (units in ppm)

Table 28: Mean element content and single standard deviation ranges of stream sediment samples draining different lithologies in Lusaka East.

6.3.2 Results of R-mode factor analysis of drainage sediment data and description and discussion of R-score distributions

Factor models extracting from three to six element associations are shown in table 29. From a background knowledge of the geology and the experience from the Provincial and Kadola factor solutions, the four factor model explaining 81% of the inter-element correlation was selected for the computation of the R-scores. The communalities for each of the elements (Table 30) show that most of the elements have more than 70% of their inter-correlation explained by the four factor model. Only copper has a communality below 0.7 of 0.63 which indicates that 63% of copper inter-correlation with other elements has been accounted for.

Element	Communality
Co	.85
Cu	.63
Cr	.76
Fe_2O_3	.86
Ga	.74
Mn	.87
Ni	.90
Pb	.88
Ti	.86
V	.72

Table 30: Communalities of the elements in the four factor model extracted from the Lusaka East drainage sediment data.

It was considered that the element associations would reflect the following features: (a) the Ni-Cr-Co-Cu-V-Fe_2O_3 association would reflect the basic rock units since they are elements which are held preferentially in the mafic minerals, (b) the Pb-Ga association would reflect the granitic rock units since Pb and Ga are both held preferentially in feldspathic minerals, (c) the Mn-Fe_2O_3-Co-V association

Factor Model Factor Associations	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for
1	Ni Cr Co Cu V Ti Mn Ga	.9 .8 .8 .8 .7 .6 .4 .3	40	Ni Cr Co Cu V Fe_2O_3	.9 .8 .7 .5 .4 .4	31	Ni Cr Co Cu V Fe_2O_3	.9 .7 .7 .4 .4 .4	30	Cr Ni Co	.8 .7 .5	19
2	Pb Ga	.9 .7	14	Pb Ga	.9 .9	14	Pb Ga	1.0 .3	11	Pb	1.0	11
3	Fe_2O_3 Mn V Ti	.9 .5 .3 .3	17	Mn Fe_2O_3 Co V	.9 .6 .4 .4	21	Mn Fe_2O_3 Co V	.9 .5 .4 .3	19	Mn Fe_2O_3 Co	.9 .4 .3	15
4				Ti Ga Cr Cu V	.8 .4 .3 .3 .3	15	Ti Cr	.8 .3	11	Ti	.8	10
5							Ga Cu V	.8 .5 .4	14	Cu V Ni Fe_2O_3 Co	.8 .7 .5 .5 .4	25
6										Ga	.9	10
Total % data correlation accounted for			71			81			85			90

Table 29: Element associations and loadings of different factor models extracted from the drainage reconnaissance data from Lusaka East (987 samples)

would reflect a secondary environmental feature particularly where there are underlying basic rocks because manganese and ferric iron are known to be strongly affected by differences in the secondary environment, and (d) the Ti-Ga-Cr-Cu-V association would reflect the schistose units since similar associations extracted from Kadola and Provincial data appeared to be related to schists. As with the treatment of factor solutions from the Kadola and Provincial data only elements with loadings of 0.3 or greater were regarded as significant elements in each association. This is used as a useful approximation of significant level of loading based on element variations with R-score variations. These mean element levels with R-score. value have been calculated and will be discussed in the following sub-sections on each association (Table 31, (a-d)).

(i) Ni-Cr-Co-Cu-V-Fe_2O_3 association

This association has strong loadings of nickel, chromium and cobalt with somewhat weaker copper, vanadium and ferric iron loadings (Table 29). It is the dominant first factor association accounting for most of the data correlation from the 3-5 factor model. In the sixth factor model Cr-Ni-Co remain as a strong association and Cu-V-Ni-Fe_2O_3-Co split to form another association. All the significantly loaded elements in the factor solution show a reasonable decrease in mean value with decreasing R-score value (Table 31(a)).

The distribution of Ni-Cr-Co-Cu-V-Fe_2O_3 R-scores (Fig. 48) shows that samples with high R-scores (greater than 0.5 and often greater than 1.0) occur mostly in the main belts of basic rocks. The contoured patterns of high values trend in an east to west and south-east to north-west direction across the centre of the field

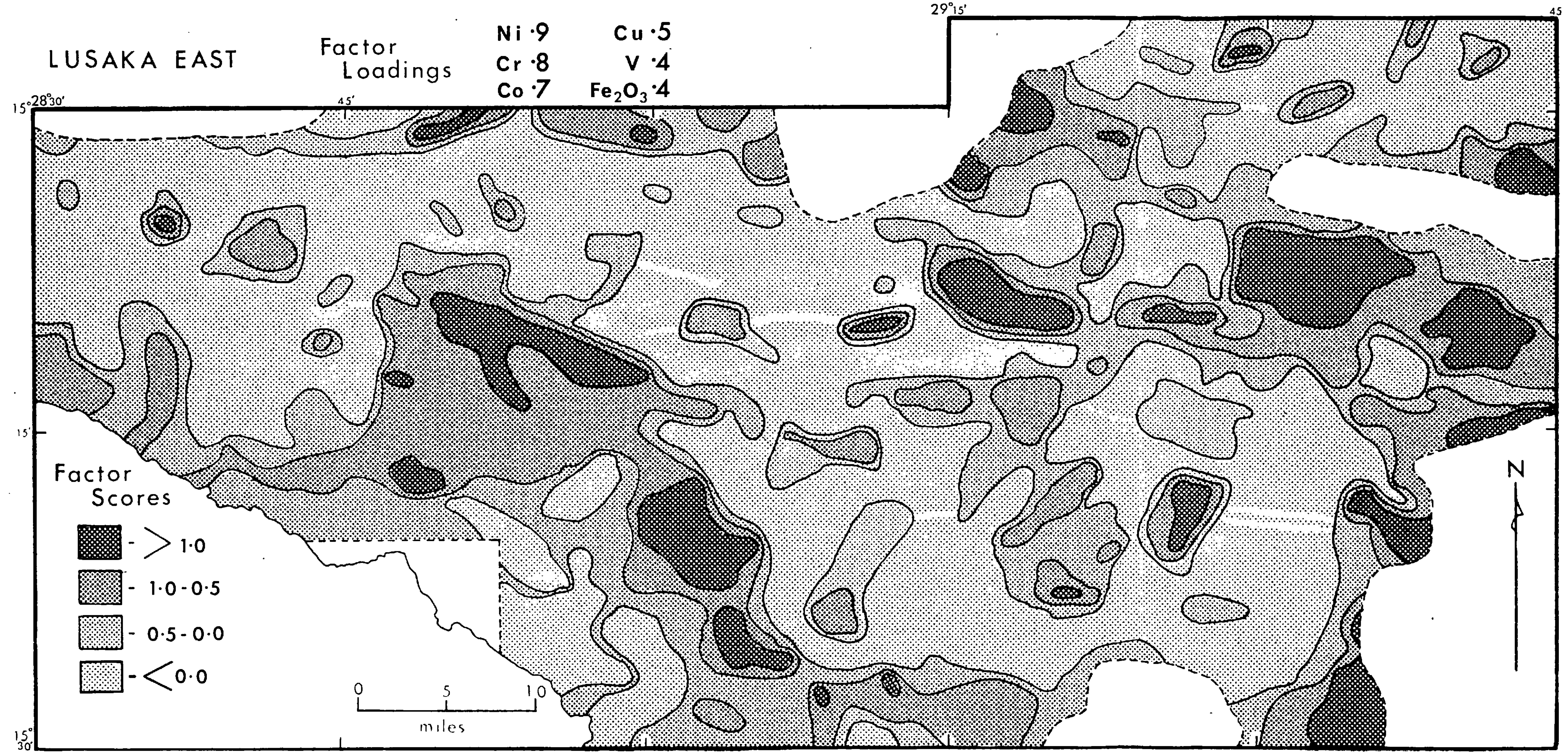

Fig: 48 Distribution of Ni-Cr-Co-Cu-V-Fe$_2$O$_3$ R-scores

Factor Scores

Element	Loading	>2.0	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0 <-2.0
Ni	.9	110	55	35	24	16	11	5	4
Cr	.8	380	160	90	65	60	50	40	18
Co	.7	65	45	35	21	17	13	7	4
Cu	.5	45	40	35	14	8	5	3	2
V	.4	590	270	130	100	80	65	50	40
Fe_2O_3	.4	14.5	10.5	7.6	5.3	4.7	3.6	2.8	2.9
Ti	.1	9800	8500	8000	6600	7000	6000	5400	4000
Ga	.1	18	15	13	12	9	10	9	12
Mn	.003	1300	1000	1000	700	600	600	600	500
Pb	-.02	15	13	16	14	14	13	13	13
No. of samples		10	21	19	25	24	22	23	13

(all units in ppm except Fe_2O_3 which is a %)

Table 31: Mean element values of samples with varying R-scores of the different associations extracted from the drainage reconnaissance data from Lusaka East.

(a) Ni-Cr-Co-Cu-V-Fe_2O_3 association

area and in a north-south direction in the east of the field area parallel to the general structural trends. An exception to this general correspondence is a pattern of high R-scores over an area mapped as granite in the centre of the field area just west of the road to Old Musangombe village. Assuming high R-scores in this association to reflect basic rocks this pattern can be considered anomalous in the sense that it indicates a lithology not previously mapped. There are also a number of smaller areas of 1 to 3 samples with high R-scores occurring over rock types other than basic.

The general association of elements known to be relatively high in mafic minerals, and the correspondence of most of the samples with high R-scores with the known occurrences of basic rocks, supports the hypothesis that the Ni-Cr-Co-Cu-V-Fe_2O_3 association reflects the basic rock units in Lusaka East. The high R-scores over units other than basic rocks suggests that the geologic map in these areas may be incorrect.

(ii) Pb-Ga association

Pb-Ga forms a relatively strong association with loadings of 0.9 and 0.6 respectively. It is a consistent association extracted from the 3-5 factor model, with Ga separating off on its own in the 6 factor model. It accounts for 14% of the data correlation. Both lead and gallium have a consistent decrease in mean element value with decreasing R-score value (Table 31(b)). The variations of the mean element values for lead and gallium between consecutive R-score classes is rather low because the overall range of these two elements is relatively small.

Factor Scores

Element	Loading	>2.0	2.0–1.0	1.0–0.5	0.5–0.0	0.0–-0.5	-0.5–-1.0	-1.0–-2.0	<-2.0
Pb	.9	40	30	19	15	13	10	6	5
Ga	.6	24	16	14	12	11	9	7	3
Co	.05	22	19	17	22	20	17	15	7
Ni	.02	19	17	18	23	18	17	15	6
V	.01	95	95	90	110	90	110	90	45
Ti	.01	6300	6300	6400	7600	7400	7500	6800	4000
Cu	-.01	10	10	9	12	13	12	8	2
Mn	-.01	490	640	640	680	730	710	510	310
Fe_2O_3	-.02	4.8	4.8	4.6	5.5	5.7	5.8	5	2.3
Cr	-.02	65	71	55	80	70	80	60	30
No. of samples		25	22	19	24	26	21	20	18

(All units in ppm except Fe_2O_3 which is a %)

Table 31(b): Pb-Ga association

The distribution of Pb-Ga R-scores (Fig. 49) shows that samples with R-scores greater than 0.5 occur in the main areas of granite. The contour outlining samples of zero R-scores and greater follow more closely the boundaries of the granite, but tend to overlap onto the schistose areas. There is an anomalous area with R-scores greater than 1.0 over an area mapped as schist to the west of the unsampled Mwapula valley in the north of the field area.

The distribution of the high Pb-Ga R-scores over granitic rock units confirms the expected correlation of the Pb-Ga association with granite. Assuming this relationship to be correct the high Pb-Ga R-scores over the schists are probably due either to incorrect geologic mapping or possibly mineralisation.

(iii) Mn-Fe_2O_3-Co-V association

Manganese is the strongest member of this association with a loading of 0.9 compared to Fe_2O_3-Co-V which only have loadings of 0.5, 0.4 and 0.4 respectively. It is a fairly consistent association since it is extracted in the 3 to 6 factor models with only minor changes (Table 29). It accounts for 21% of the data correlation. Manganese and cobalt mean values decrease consistently with decreasing R-scores (Table 31(c)). Ferric iron and vanadium, however, have a reversal in value between the R-scores greater than 2.0 and 2.0 to 1.0. This reversal indicates that the samples with the highest manganese samples do not have equivalent high ferric iron or vanadium values although they correlate over the lower range of manganese values. This suggests that there may be more than one feature giving rise to high manganese values in the drainage sediment.

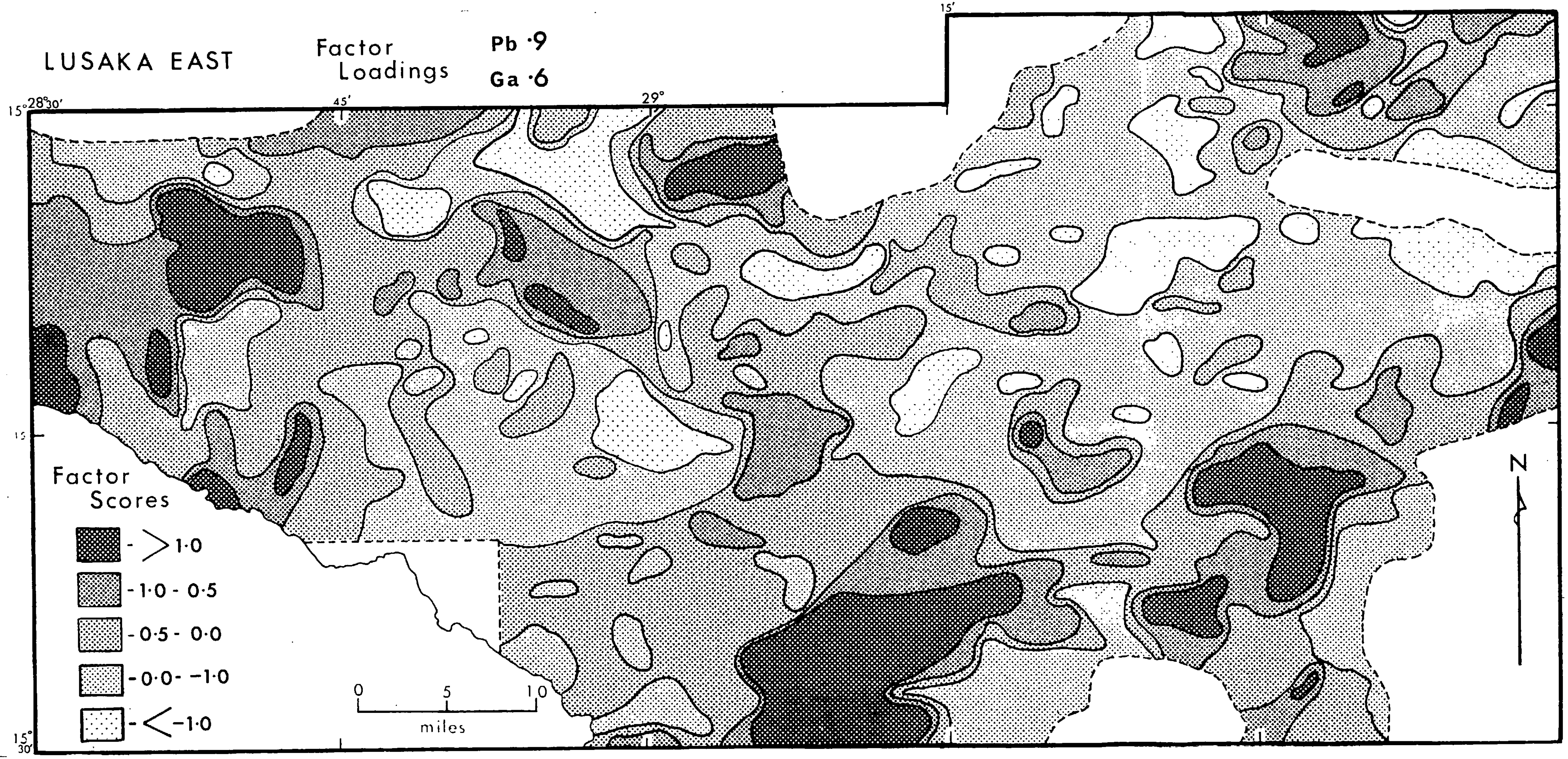

Fig: 49 Distribution of Pb-Ga R-scores

Factor Scores

Element	Loading	>2.0	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0 <2.0
Mn	.9	2400	1400	1100	750	550	390	180	65
Fe_2O_3	.6	13	13.5	8.1	5.5	3.7	3.5	2.7	1.7
Co	.4	70	40	29	23	18	15	9	8
V	.4	210	360	140	90	75	75	60	40
Cu	.2	40	50	20	11	6	7	4	2
Ga	.2	12	15	13	11	10	12	10	7
Ti	.1	6000	9000	8000	7500	7000	5700	5000	4000
Ni	.07	30	40	26	19	18	14	12	10
Pb	-.06	11	13	15	15	14	14	12	14
Cr	-.1	50	110	95	65	75	60	50	45
No. of samples		8	20	20	21	21	20	21	48

(all units in ppm except Fe_2O_3 which is a %)

Table 31(c): Mn-Fe_2O_3-Co-V association

Distribution of the Mn-Fe_2O_3-Co-V R-scores (Fig. 50) shows that the highest contour (greater than 0.5) includes most of the basic rock occurrences, but the contours of this and other intervals do not follow the geologic boundaries. The low R-score patterns (below -1.0), on the other hand, outline the flatter parts of Lusaka East where the drainages are poorly drained swampy dambos. The areas with R-scores of zero or greater, on the other hand, tend to occur mainly in the more rugged areas where the drainages are more often incised streams with sandy sediment.

This relationship of higher Mn-Fe_2O_3-Co-V R-scores with the drier sandier drainages in the more incised areas substantiates the interpretation that this association is a secondary environmental feature. Unfortunately, there were no detailed notes available of the drainage sample types, and so this conclusion could only be tentative, relying on the approximate knowledge of the distribution of drainage types. There is clearly, however, a relationship of this association with the basic rock units. This is to be expected both from their higher manganese content and their inhibiting effect on the mobility of these elements due to an increase of the pH in the overlying secondary environment.

(iv) Ti-Ga-Cr-Cu-V association

Titanium is the dominant element in this association with a loading of 0.8. The other elements having comparatively low loadings of 0.4 for gallium and 0.3 for chromium, copper and vanadium. It accounts for 15% of the data correlation which is relatively low considering the number of elements in the association. The relative weakness of the association is also demonstrated by its instability

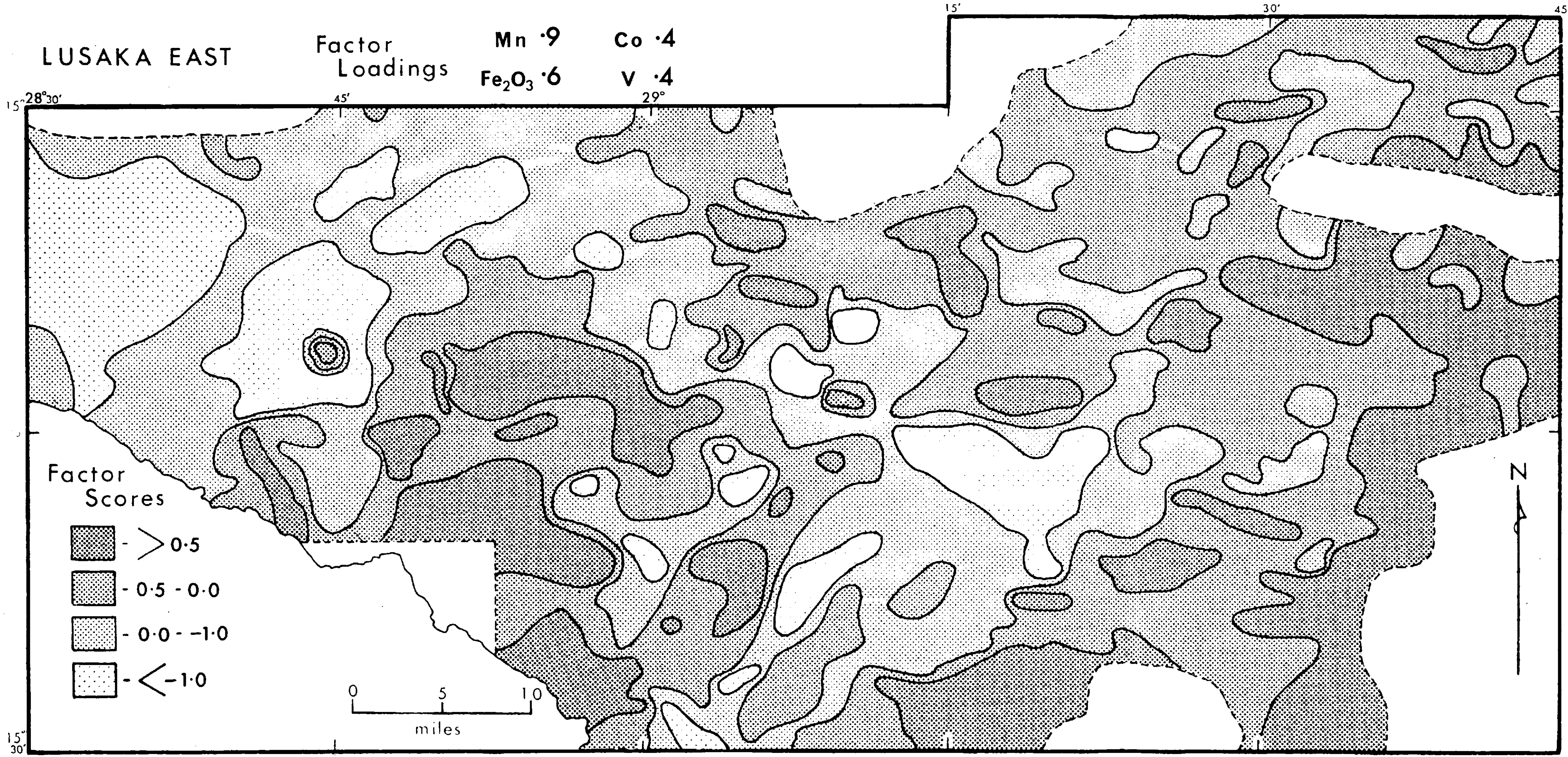

Fig: 50 Distribution of Mn-Fe_2O_3-Co-V R-scores in the 5 and 6 factor models (Table 29). Similarly, the lack of consistent decrease in gallium, chromium, copper and vanadium with decreasing R-scores (Table 31(d)), indicates that there are other features controlling these elements besides the one reflected in this association. These features are reflected in the other associations in which these elements are included.

The distribution of the R-scores (Fig. 51) shows that samples with high R-scores (greater than 0.5) occur mainly over schistose and basic rock units. Samples with low R-scores (below -1.0) occur particularly over the granites.

There are no high Ti-Ga-Cr-Cu-V R-scores which do not occur over schists, however, there is an area of anomalously low R-scores over the schistose units in the Buffalo Hill area in the northeast of the field area.

These R-score distributions confirm the original suggestion that the Ti-Ga-Cr-Cu-V association reflected the schistose units. The high R-scores over the basic rock units confirm that other features besides schistose rocks are influencing the association and are probably partly responsible for its instability as a group of elements.

6.3.3 Relationship of minor-element associations in rocks and soils to those in drainage sediments

The R-score distributions of the associations extracted from the original drainage samples, as described in the former section, correspond in general to the features to which they have been ascribed. The geologic features have been taken from the geologic map and the secondary environmental features from a background knowledge of the area. Although the mapped geology is probably reliable in the

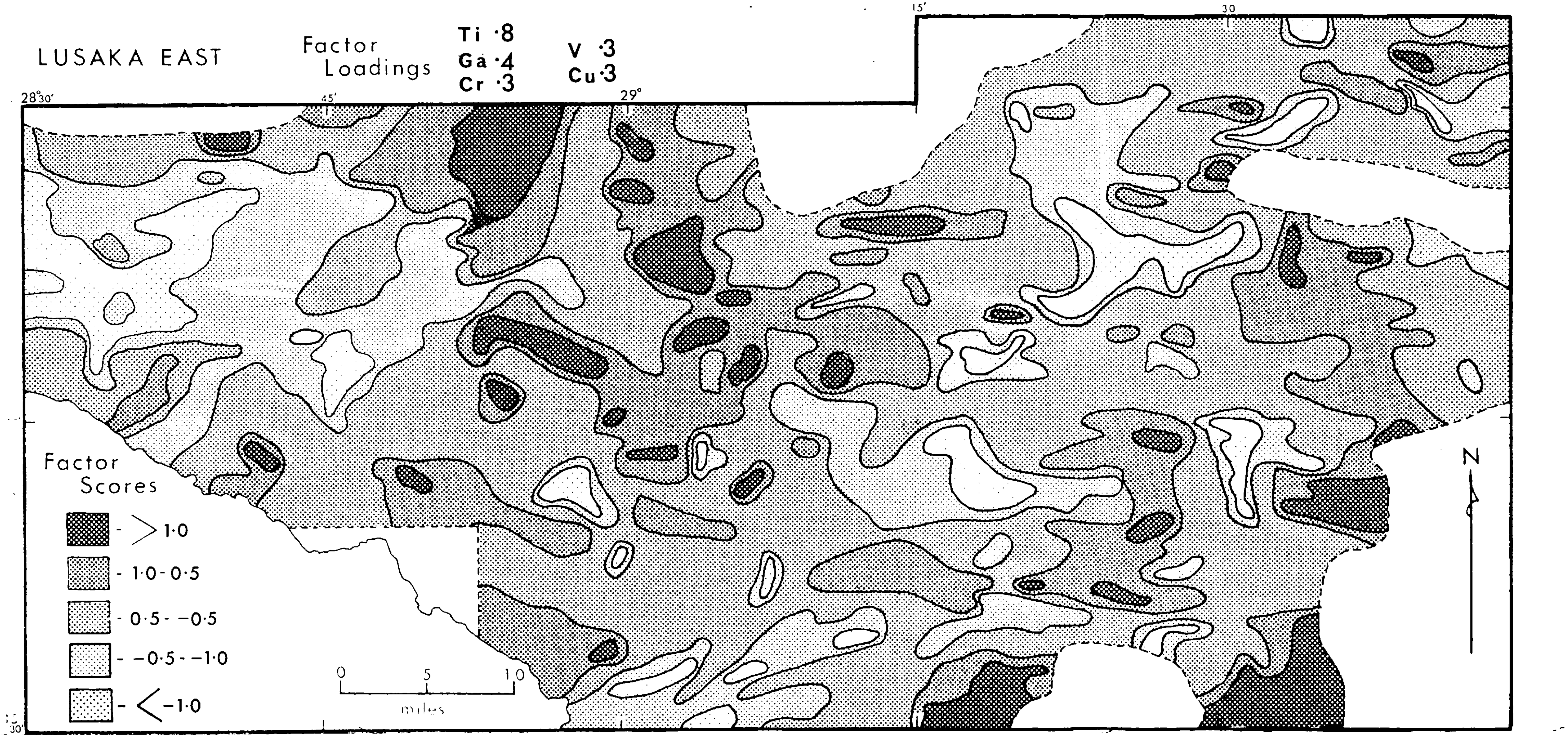

Fig: 51 Distribution of Ti-Ga-Cr-V-Cu R-scores

R-Scores

Element	Loading	2.0	2.0	1.0	0.5	0.0	-0.5	-1.0	-2.0 2.0
Ti	.8	10400	10000	9000	7700	6000	4800	3800	2500
Ga	.4	20	16	14	10	11	9	9	5
Cr	.3	130	140	75	80	65	50	35	22
Cu	.3	27	27	15	9	12	7	4	2
V	.3	150	210	130	85	80	80	55	35
Fe_2O_3	.2	5.7	8.1	6.8	5.3	4.5	4.1	2.9	1.9
Mn	.05	490	730	870	800	690	520	490	210
Ni	-.03	9	35	20	17	19	14	12	9
Co	-.05	17	26	22	18	18	16	15	8
Pb	-.08	9	12	16	14	15	14	16	19
No. of samples		5	24	21	22	26	19	22	17

(all units in ppm except Fe_2O_3 which is a %)

Table 31(d): Ti-Ga-Cr-Cu-V association

incised areas of reasonably good outcrop this cannot be said of the areas of poor outcrop.

In order to confirm that the suggested relationships between the element associations extracted from the drainage sample data and the primary and secondary features are correct, and to establish the significance of the anomalous R-score patterns, traverses over critical patterns were made taking rock, soil and replicate drainage samples. The selection of the critical patterns for resampling, and the sampling techniques were the same as those used in the Kadola area (6.2.4). In most places, rock sampling was facilitated by good outcrop.

R-mode factor analysis of the minor-element data from these different sample media have extracted element associations broadly similar to those extracted from the drainage sample data (Table 32). The four factor models were chosen from the soil data and the five factor models from the rock and replicate drainage samples as extracting the most comparable associations, and explaining a similar percentage of the data correlation. The similarities and differences in the associations will be discussed and explained in the following subsections.

(i) Cr-Ni-V and associated elements

An association including chromium, nickel and vanadium is extracted from all the different sample media. It is the dominant association explaining a maximum of the data correlation in all sample media. The Ni-Cr-Co-Cu-V-Fe_2O_3 association extracted from the original drainage sediment samples was related to the basic rock units. Other elements in the equivalent associations extracted from the data of different sample media are all those which would be expected to be

Rocks			Soils			Drainage Sediment					
						(Initial samples)			(replicate samples)		
Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for	Element	Loading	% data correlation accounted for
Cr Ni Ga V	1.0 .6 .4 .4	20	Cr Ni V Co Cu	.9 .8 .6 .4 .3	29	Ni Cr Co Cu V Fe_2O_3	.9 .8 .7 .5 .4 .4	31	Ni Co Cr Zn V	.9 .8 .7 .5 .4	27
Pb Ga Mn	1.0 .5 .5	15	Pb Ga	.9 .7	17	Pb Ga	.9 .6	14	Ga Pb V	.9 .7 .5	17
Zn Mn Co Ga	1.0 .6 .5 .3	19	Mn Zn Cu Co V Ga	.8 .7 .7 .6 .4 .3	25	Mn Fe_2O_3 Co V	.9 .6 .4 .4	21	Mn Zn	.9 .4	12
Ti V	1.0 .6	16	Ti Mn	.8 .4	11	Ti Ga Cr Cu V	.8 .4 .3 .3 .3	15	Ti Cr V	.9 .5 .3	14
Cu Co Ni	1.0 .4 .3	15							Cu V	.9 .3	13
Total % data accounted for		85			82			81			83
No. of samples	169			186			987			161	

Table 32: Element associations, loadings and percentage data correlation accounted for by each factor from the data of the different sample media from Lusaka East.

high in the mafic minerals. The differences in the associated elements with weaker loadings from the different sample media is probably due to a combination of a redistribution in the secondary environment and a differing proportion of samples influenced by the various controlling bedrocks. In particular, cobalt and copper are most commonly included in the association, in the soil and original drainage sample associations, and cobalt in the replicate drainage samples. These differences are probably mainly due to the greater proportion of rock and replicate drainage samples being taken from areas of copper mineralisation than soil and original drainage samples. This has resulted in a low copper correlation with the other elements usually high in mafic minerals, and its extraction as an association with low loadings on cobalt and nickel from the rock sample data and vanadium from the replicate drainage sample data. When five factors are extracted from the original drainage sediment and soil data, copper is still associated with the main mafic elements (Table 29).

The inclusion of gallium in the Cr-Ni-Ga-V association from the rock sample data and its omission in the equivalent association from the other sample media is perhaps a secondary re-distribution of gallium. The mean gallium content of the basic schists is considerably enhanced (Table 33). The inclusion of zinc in the Ni-Co-Cr-Zn-V association extracted from the replicate drainage samples would seem reasonable from a consideration of its affinity to basic rocks (Table 33). It is surprising that it is not also included with the Cr-Ni-Ga-V association from the rock data and the equivalent soil data. Presumably this is due to its very strong affinity to manganese which has resulted in separating zinc from its slightly weaker association with the other mafic elements. (N.B. Zinc was not included as

Lith-ology		Basic Rocks					
		Epidosites	Biotite & Horneblende schists	Granites and granite gneisses	Mica Schists	Micaceous Quartzites	Quartzites
Co	GM*	26	35	16	22	16	16
	Range+	16-40	24-55	10-23	13-35	10-26	11-25
Cr		50	70	45	60	45	40
		30-80	40-130	30-60	35-100	35-65	35-55
Cu		26	35	13	20	14	13
		10-65	11-100	8-21	8-50	8-26	6-27
Ga		90	40	16	40	8	3
		50-150	20-90	8-35	20-75	3-23	2-7
Mn		700	300	140	140	35	14
		450-1200	150-700	50-400	50-400	7-200	4-50
Ni		70	30	4	18	6	4
		30-170	6-150	1-13	5-65	2-18	2-7
Pb		15	4	8	6	4	2
		6-35	2-8	4-16	2-13	2-7	1-4
Ti		7000	8000	4500	8000	6000	4500
		4500-11000	5000-13000	3500-6000	5000-13000	4000-9000	3000-6000
V		55	60	7	55	13	6
		25-110	17-220	2-18	18-170	4-50	3-15
Zn		30	55	30	30	16	14
		15-60	27-100	15-60	13-80	9-30	9-20
No. of samples		14	24	50	30	36	15

*Geometric mean +Single standard deviation range

Table 33: Mean element content and single standard deviation ranges of rock samples of different lithologies from Lusaka East (units in ppm)

a variable in the initial drainage sample data, and ferric iron was not included in the rock, soil and replicate drainage sample data.)

Rock samples with the highest Cr-Ni-Ga-V R-scores are the biotite and horneblende schists and the epidosites and metamorphosed volcanics (Table 34). These are the lithologies which are loosely termed basic rocks. Similarly, the soils with the highest Cr-Ni-V-Co-Cu association R-scores overlie basic rocks (Table 35). There is no doubt, therefore, that the associations from the various sample media which include Cr-Ni-V, are related to basic rocks.

The high Ni-Cr-Co-Cu-V-Fe_2O_3 R-scores over an area mapped as granite is, therefore, anomalous as previously suggested (Fig. 52). A traverse over the area revealed only a little outcrop, in the north-east of the pattern, of foliated granite gneiss interleaved with quartzite and micaceous layers. Samples of these lithologies and soil samples in the vicinity of these outcrops gave low R-scores for the mafic element associations. The replicate drainage sediment samples, however, confirmed the original results and had high Ni-Co-Cr-Zn-V R-scores. This result and the observed variation in the layering of the granitic rocks suggests that there are also more basic, biotite or hornblende layers. These would be less likely to outcrop because of their relative weakness to resist weathering. Towards the south-west and central part of the pattern, the soil changes from light orange clayey sand to a brighter red silty sand and the vegetation becomes a thick thorny impenetrable scrub. Soil samples from this redder soil type have much higher Cr-Ni-V-Co-Cu R-scores than those elsewhere. Because of the poor outcrop and access in this area the geology as shown on map is inferred (G. Simpson, Geol. Surv. Zambia, pers. comm.).

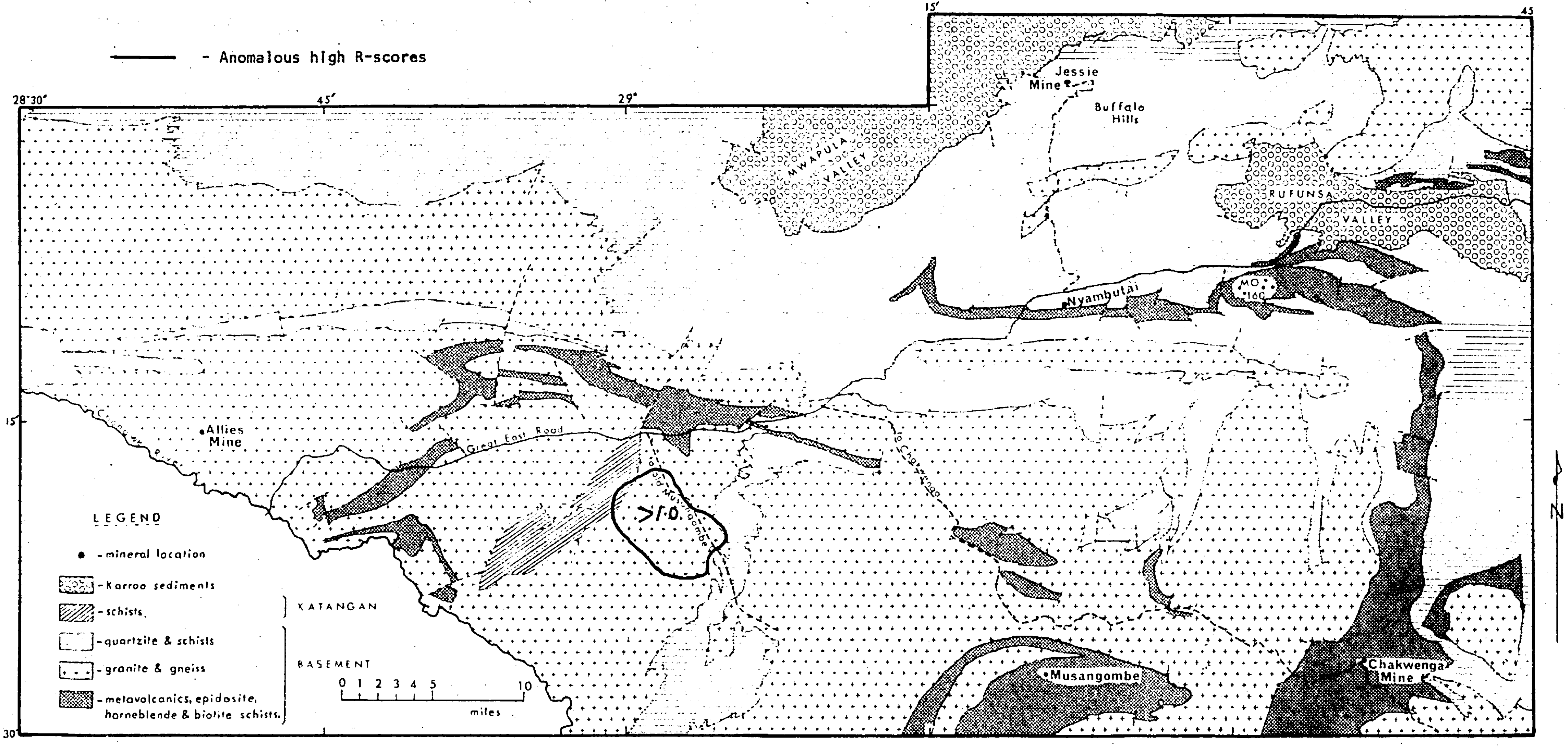

Fig: 52 Re-sampled Ni-Cr-Co-Cu-V-Fe_2O_3 R-score pattern

Lithology Factor associations	Basic rocks					
	Epidosites	Biotite Horneblende schists	Granites and granite gneisses	Mica schists	Micaceous Quartzites	Quartzites
Cr-Ni-V-Ga	.6	.8	-.5	-.2	-.3	-.6
Pb-Ga-Mn	1.5	-.3	.4	-.2	-.5	-.1
Zn-Mn-Co-Ga	.4	1.0	0.1	.2	-.2	-.3
Ti-V	.5	.6	-.6	.7	-.1	-.7
Cu-Co-Ni	.6	.8	-.5	.1	-.2	-.3
Number of samples	14	24	50	18	36	15

Table 34: Mean factor association R-scores of rock samples of different lithologies from Lusaka East.

Underlying Lithologic Unit Factor associations	Basic rocks	Quartzites	Granites and Gneisses	Schists	Siliceous Schists
Cr-Ni-V-Co-Cu	1.1	-.7	-.2	-.3	-.4
Pb-Ga	-.2	-.6	.9	.3	-.5
Ti-Mn	.2	.1	-.4	.6	.5
Mn-Zn-Cu-Co-V-Ga	.8	-.5	-.1	.1	-.2
Number of samples	28	27	60	11	16

Table 35: Mean factor association R-scores of soil samples overlying different lithologies in Lusaka East.

From this above evidence, therefore, there seems little doubt that the high Ni-Co-Cr-Cu-V-Fe_2O_3 R-scores in this area has indicated an area of basic rock occurrences previously thought to be granitic, and that there are probably basic layers interfoliated with the granite in the north-east of the pattern.

(ii) Pb-Ga association

A strong Pb-Ga association is extracted from the data of each of the sample media (Table 32). Manganese is included in the Pb-Ga association extracted from the rock sample data and vanadium is included with the Pb-Ga association from the replicate drainage sample data.

The correlation of manganese with lead and gallium is due firstly to the relatively high manganese contents in many of the granitic rock samples. This is a common feature in igneous rocks of somewhat more intermediate composition than true granites (Rankama and Sahama, 1949). Secondly, it is a reflection of the high lead values in the epidosites. Epidote is known to incorporate up to 100 ppm of lead as well as manganese (op. cit.). The lack of manganese in the Pb-Ga association extracted from the soil and drainage sample data is due probably to a combination of features. Firstly, the epidosites are resistant to weathering and outcrop mainly along the ridges where they contribute little material to the stream sediment. Secondly, because epidosites are resistant to weathering they outcrop more often than the softer surrounding rocks and have probably been sampled more often than their areal extent justifies. The drainage sediment samples being more evenly distributed would have better sampling representivity. Thirdly, there has probably been some redistribution of the elements in the secondary environment, either the leaching of manganese from drainage sediments and soils overlying the granitic rocks high in manganese, and, or the leaching of lead from sediments derived from epidosites. Of the 9 soil samples known to overlie epidosite only 2 have lead values of 20 ppm, 2 have values of 5 ppm and the rest are below the 5 ppm detection limit. The same number of soil samples over schists have a similar proportion of detectable lead values. This suggests that there is leaching of lead from the soils over epidosites. Although the number of samples is inadequate to prove this, this feature would help explain the omission of the manganese in the Pb-Ga associations extracted from the drainage sediment and soil data.

The inclusion of vanadium in the Pb-Ga association extracted from the replicate drainage sediment sample data is probably due to the strong correlation of gallium for vanadium, which is from their sympathetic high values in schists.

Rock samples with the highest mean Pb-Ga-Mn R-scores are firstly epidosites and secondly granites (Table 34). All the other rock types have negative mean R-scores in this association. Soil samples with the highest Pb-Ga R-scores are those overlying granitic rocks (Table 35). There is little doubt, therefore, that samples with high Pb-Ga R-scores usually indicate granite rocks, although they can also indicate the presence of epidosites.

An area of high Pb-Ga R-scores occurs over an area mapped as a schistose unit along the north central edge of the field area just west of the Mwapula valley (Fig. 53). Follow-up work in this area showed that the bedrock was mica schists often with garnet and staurolite porphyroblasts. These schists were interleaved with

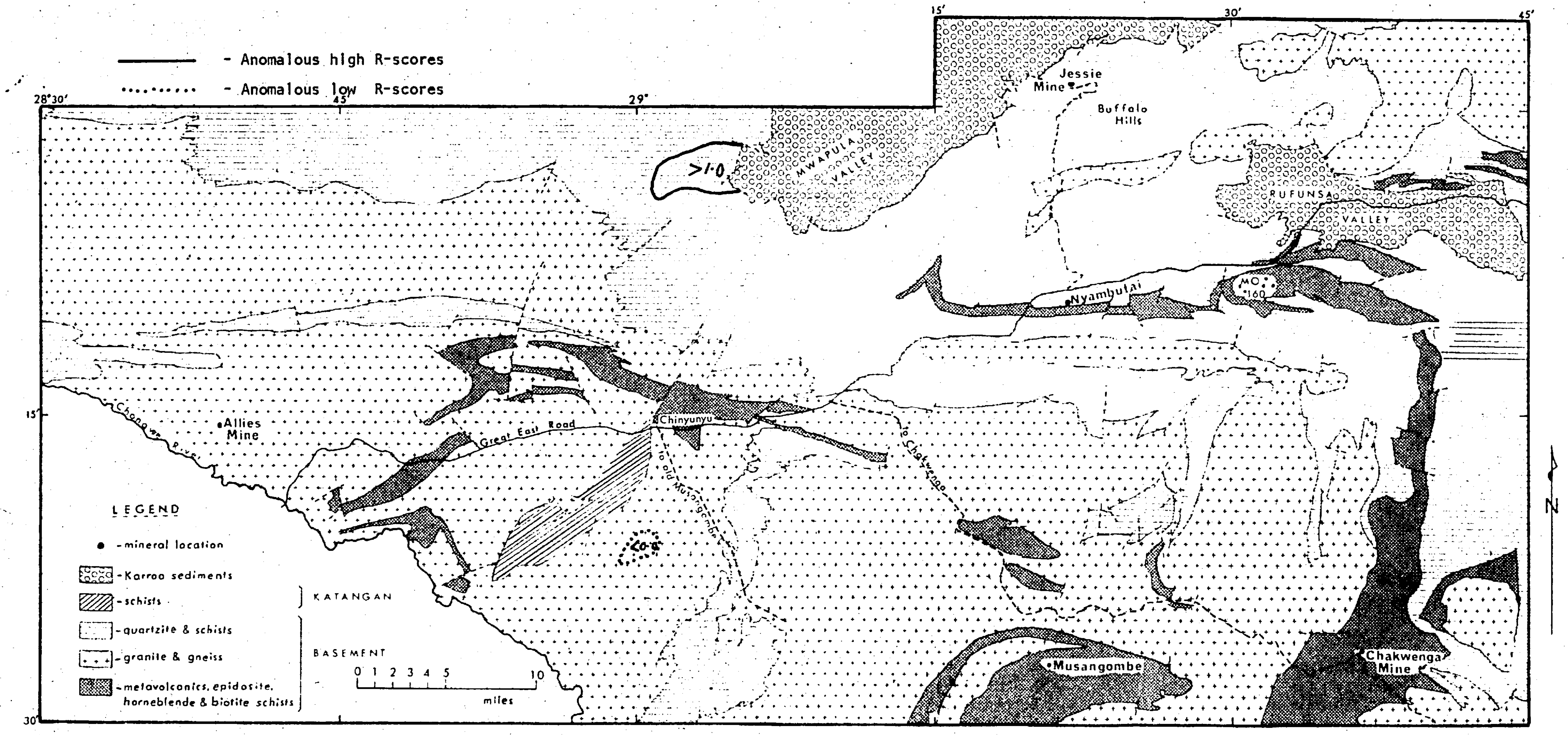

Fig: 53 Re-sampled Pb-Ga R-score pattern quartzite and micaceous quartzite. Outcrop was good but access was poor and only a limited amount of sampling in the south of the anomalous area could be accomplished. The streams were incised and most of their sediment content was composed of quartz, muscovite, minor biotite and rock fragments. The erosion was mostly mechanical. No feldspars, which might have been derived from granitic rocks were seen in the stream sediments. None of the replicate drainage samples or soil samples had lead values above the detection limit. Three out of the nine rock samples from the area have lead values from 20-40 ppm. The three samples with the lead values were siliceous muscovite schists with minor amounts of biotite, and one of them had garnet prophyroblasts. The other six samples are micaceous quartzites. The explanation for these enhanced lead values in the micaceous schists could be that they are phyllonitic schists derived from sheared granites. Simpson (1967) has defined extensive areas of these phyllonitic schists. This is an unlikely explanation, because the quartzite and schistose layering suggests that the rocks were of sedimentary origin prior to being metamorphosed. Simpson has not identified the schists in this area as being phyllonitic schists. Lead has possibly been introduced into highly metamorphosed schists. Since, however, the grade of metamorphism is thought to increase southwards, and there are many schists to the south which do not have a similar high lead content, this does not seem a likely explanation either.

One of the original drainage sediment samples with a relatively high lead value of 20 ppm was reanalysed and gave a value of 30 ppm which suggests that the original analyses were correct.

The inability, therefore, of the replicate drainage sediment or soil samples to reproduce the lead values in the original drainage sediment samples throws some doubt on the sampling or sample preparation of the original samples.

It has not been possible to carry out adequate rock sampling to show that there is without any doubt a raised lead background value at least in the schists. This anomalous Pb-Ga R-score pattern remains therefore unexplained, but is of doubtful significance.

In conclusion, it is clear that a Pb-Ga association is related to granitic rocks. The presence of epidote rich rocks, however, can seriously complicate this simple explanation because of the ability of epidote to incorporate lead. For various reasons already noted, however, the high lead in the epidote rich rocks has not been reflected in the soils or stream sediments derived from them.

(iii) Manganese and associated elements

An association dominated by manganese is extracted from the data from the soil and stream sediment samples. When zinc is included as a variable it is always extracted in association with the manganese factor. Similarly, cobalt is usually extracted with manganese (Table 32). In the Mn-Zn association extracted from the replicate drainage samples cobalt has a loading of 0.2 suggesting at least some correlation of cobalt with manganese. The equivalent manganese association extracted from the rock sample data appears to be a Zn-Mn-Co-Ga association. Vanadium is included with the manganese association extracted from the initial drainage sample data. It is probably not included in the manganese association from the replicate drainage samples and rock samples because of the lack of ferric iron as a variable. Vanadium is usually highly correlated with ferric iron, therefore, when ferric iron is included in a factor association it usually takes vanadium with it into the association. Vanadium and copper are also included in the manganese association from the soil sample data. This association, however, is very unstable and in the 5 factor model manganese is extracted on its own. This suggests that manganese is being concentrated on its own in the soils.

The Mn-Fe_2O_3-Co-V association from the initial drainage sample data was related to stream sediments draining basic rock units and to drier stream beds where manganese is enriched. The relationship of the manganese associations to the basic rocks is confirmed by the high mean Zn-Mn-Co-Ga R-scores of basic rock samples (Table 34) and the higher mean Mn-Zn-Cu-Co-V-Ga R-scores of soil samples overlying basic rock units (Table 35).

In order to test the secondary concentration of manganese, replicate drainage samples were taken from dambos and sandy sediment streams which drained similar granitic or schistose lithologies. Often these samples were from adjacent valleys draining the same outcrops. The mean element content of these different types of drainage sediment show that manganese is enhanced in the sandy stream sediments by more than twice the value in the dambo sediment (Table 36). All the other elements, however, with the exception of titanium, tend to be reduced in value in the sandy stream sediments.

These values indicate that none of the other elements are concentrated with manganese in the sandy drainage sediments. The correlation, therefore, of zinc, cobalt and the other elements with manganese, which result in their extraction in the same factor association is due to their sympathetic high values in basic rocks and not enrichment in the secondary environment as in the U.K. sediments (Horsnail, 1968). In the U.K. the precipitating manganese hydroxides

Drainage sediment type Element	Dambo Sediments	Sandy Stream Sediments
Mn $^+$GM ≠	200 100-500	600 300-1000
Co	35 19-55	22 14-35
Cr	90 55-140	70 110-160
Cu	30 15-110	20 11-40
Ga	50 27-95	50 23-100
Ni	40 26-70	30 18-40
Pb	5 4-7	6 3-9
Ti	16,000 12,000-23,000	19,000 14,000-27,000
V	120 65-220	95 60-50
Zn	50 40-100	35 28-45
No. of samples	39	30

$^+$Geometric mean in ppm

≠ Single standard deviation range

Table 36: Mean element content and standard deviation ranges of different drainage sample types from Lusaka East.

tend to scavenge cobalt and zinc and other cations in the water-logged drainage channels. In Zambia, on the other hand, the streams are only wet for a comparatively short period which seriously inhibits the mobility of cations in solution and therefore any scavenging by manganese hydroxide.The slight enhancement of titanium in the sandy stream sediments is indicative of the residual nature of titanium bearing minerals. This relationship of titanium with manganese due to the similar residual character of the minerals bearing these elements has already been noted in the Ti-Mn associations extracted from the soil data, from Kadola and the provincial data. It is interesting to note that this Ti-Mn association is also extracted from Lusaka East soil data (Table 30).

Iron analyses are available for 12 of the dambo sediment samples and 10 of the sandy stream sediment samples. The mean ferric iron values for these samples are 5.8 and 6.4 respectively. This increase in value corroborates the sympathetic increase of manganese and ferric iron in sandy stream sediments reflected in the Mn-Fe_2O_3 association extracted from the original drainage sediment data; however, the increase and the number of samples are too small to prove this relationship conclusively.

In conclusion, therefore, the above evidence shows that manganese is greatly enhanced in value in sandy stream sediments compared to dambo sediments. In contrast, none of the other elements are similarly enhanced with manganese. The manganese associations with zinc, cobalt and other elements is, therefore, due to their sympathetic high values in basic rocks.

(iv) Titanium and associated elements

An association dominated by titanium is extracted from the data from each of the sample media (Table 32). Vanadium is consistently included with titanium in the associations from the rock and drainage sediment data. Chromium is included with the titanium association extracted from the drainage sediment data but not the rock and soil data. The lack of chromium in the titanium association extracted from the rock data indicates that they are not strongly correlated in the primary environment. Their correlation in the drainage sediment, therefore, is possibly due to the concentration of chromite and ilmenite in the stream sediments and, or their secondary concentration of titanium and chromium in the dambo clay sediments. Both elements tend to be concentrated in hyrodrolyzate sediments (Rankama and Sahama, 1949). Since gallium usually replaces aluminium in the rock forming minerals the inclusion of gallium in a titanium association further suggests the presence of schistose or argillaceous rocks. Gallium does in fact have a loading of 0.2 in the Ti-V association extracted from the rock data showing that there is, at least, some correlation. It is surprising that gallium is not extracted with the Ti-Cr-V association from the replicate drainage sample data. This is probably due to the very strong Ga-Pb association extracted as a result of the relatively greater number of samples derived from granites compared to the initial drainage samples. The inclusion of copper with the titanium association extracted from the initial drainage sediment data has already been discussed and related to the preference of copper mineralisation for schistose rock units. A copper association has been extracted from the rock and replicate drainage sample data because a fair number of samples, about 20% in the case of the replicate drainage samples, were taken from rocks and drainage sediments affected by copper mineralisation.

The Ti-Mn association extracted from the soil data has already been mentioned in connection with the manganese association. As has been suggested earlier, it is thought to be due to the resistate character of both the secondary manganese dioxide and the primary titanium bearing minerals such as ilmenite both of which become concentrated in the upper part of the soil profile, due to the eluviation of the clay minerals and leaching of elements from soluble minerals.

The Ti-Ga-Cr-Cu-V association extracted from the original drainage sediment data was related to the schistose rocks on the basis of high R-score patterns of this association corresponding to schistose rocks. Micaceous schists have the highest R-scores in the Ti-V association (Table 34). Soil samples overlying both schists and siliceous schists both have relatively high Ti-Mn R-score values compared to soils overlying other rock units (Table 35). There is little doubt, therefore, that factor associations dominated by titanium and the Ti-Ga-Cr-Cu-V association in particular does in fact reflect schistose rock units.

Two areas of anomalous Ti-Ga-Cr-Cu-V were traversed. One area was immediately north of Chinyunyu where high Ti-Ga-Cr-Cu-V R-scores occurred over an area mapped as quartzite (Fig. 54). The streams in this area are deeply incised into the quartzite ridges. Outcrop is infrequent in the valleys but the soil is red and micaceous rich whereas the soil over the quartzite tends to be pale and siliceous. This soil variation and the few outcrops suggested that the valleys follow micaceous schist units which are intimately

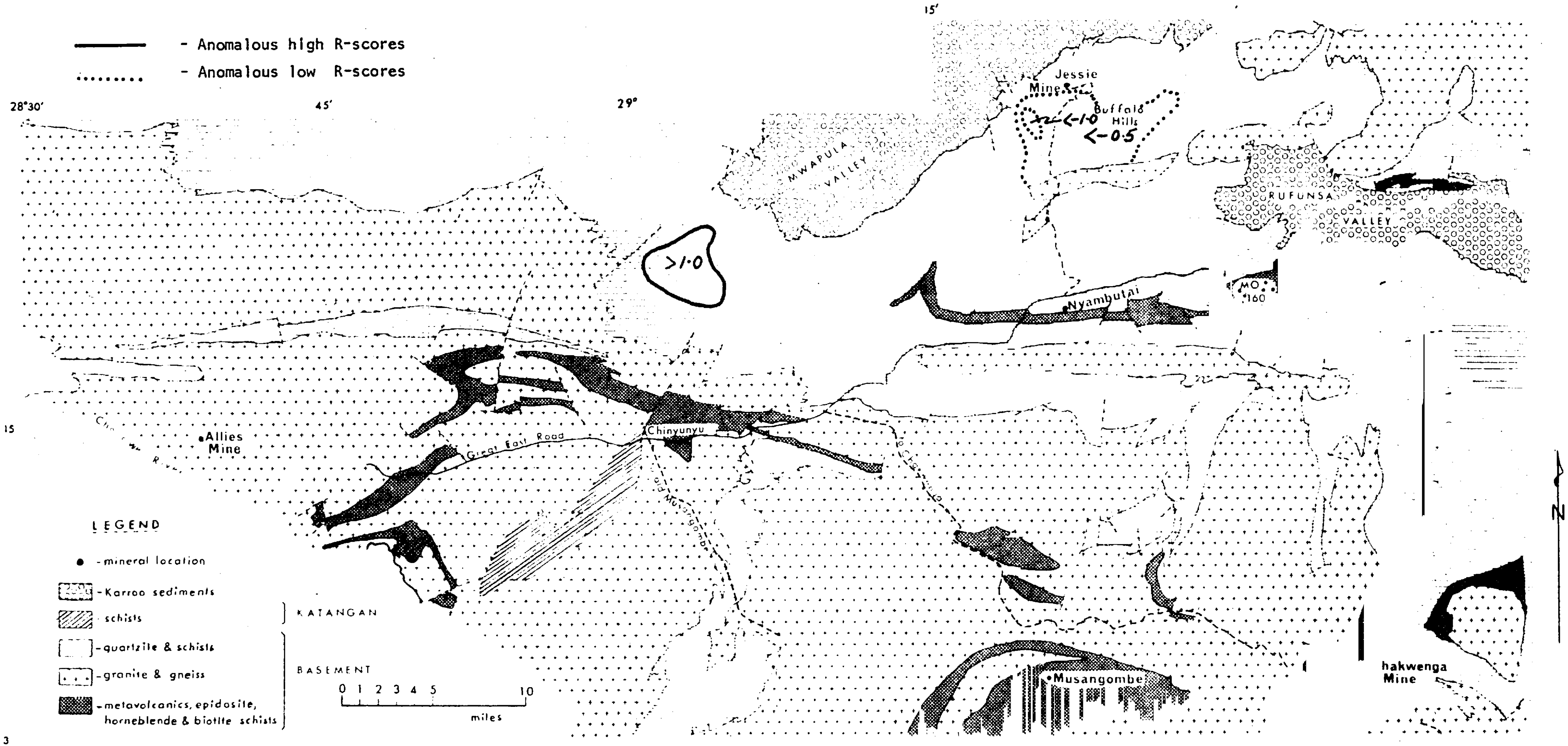

Fig: 54 Re-sampled Ti-Ga-Cr-Cu-V R-score patterns associated with the quartzite. Recent mapping by the Geological Survey has, in fact, shown schistose units along most of these drainage channels (Simpson, 1967).

A second anomalous area of low Ti-Ga-Cr-Cu-V association R-scores occurs in the Buffalo Hill area where schistose rocks have been mapped and high R-scores in this association should be expected (Fig. 54). Traversing across this area, where outcrop was relatively good, indicated that schist, phyllite, graphitic phyllite and quartzite to be interbanded. The rock, soil and replicate drainage sediment samples from the area all have relatively high titanium and vanadium results. Their similar titanium associations have corresponding high R-scores. Reanalysis of two of the original drainage sediment samples confirmed their low titanium values obtained in their initial analysis. It appears, therefore, that either the original sampling or sample preparation was incorrect, or the original samples were from streams draining unrepresentative geology. This last suggestion is possible since quartzite is often interbedded with the schistose units.

In conclusion, therefore, the rock and soil sampling shows that the Ti-Ga-Cr-Cu-V association extracted from the original drainage sediment data does in fact reflect schistose rock units in the upstream catchment area. R-scores have helped to indicate one area which was incorrectly mapped because of poor outcrop.

(v) Copper association

An association dominated by copper is extracted in the five factor model from both the rock and replicate drainage sample data. A similar association is not extracted from the initial drainage sample data until the six factor model, and from the soil sample data until the eight factor model. The reason for a copper association in earlier factor models from the rock and duplicate drainage sample data is due to their having 20% of their samples with relatively high copper values, influenced by mineralisation. In the case of the replicate drainage samples 20% of the samples had high copper values and were taken downstream from known mineralisation. In the case of the rock samples 24% of the samples had high copper values of which 17% were taken from the rocks in the vicinity of known copper mineralisation. The samples with high copper content were defined as those having R-score values greater than 0.5. This corresponded to a copper value of 50 ppm for the rock data and 60 ppm for the replicate drainage sample data. The differences between the copper associations extracted from the rock and replicate drainage sample data is not very significant. The loadings of cobalt and nickel, and vanadium with the copper associations from the rock and replicate drainage data respectively are both relatively low, and vanadium has a loading of 0.2 in the Cu-Co-Ni association from the rock sample data and cobalt and nickel have a loading of 0.1 each in the Cu-V association from the replicate drainage sample data.

In order for anything like a mineralisation factor to be extracted by R-mode factor analysis in a factor model extracting relatively few associations, it appears to be necessary for some 20% of the samples to have high element values derived from the mineralisation in question. This is unlikely to be the case in normal reconnaissance sampling where perhaps 5% or less of the samples might be expected to have their minor element content influenced by mineralisation.

6.4 RELATION OF R-MODE FACTOR ASSOCIATIONS TO MINERALOGY OF ROCK SAMPLES

During the course of evaluating the associations, extracted by R-mode analysis from the various groups of data, it has become clear that each rock type is not necessarily defined by only one factor association. For example, epidosites have relatively high mean R-scores in each of the factor associations (Table 34). Similarly, the biotite schists have relatively high mean R-scores in all the associations except Pb-Ga-Mn association (Table 34). In order for the elements to be defined in groups there should, theoretically, be some feature which controls each of the associations. Since the minor element content of rocks is controlled more by the minerals present than general rock type, it seems more probable that extracted factor associations of the minor elements reflect the minerals present. It is recognised, of course, that the mineral content determines the rock type. However, one rock type often contains one or more of the minerals present in other rock types. The rock samples from Lusaka East area were reasonably unweathered and are considered representative of the geology as a whole compared with those taken for Kadola and Provincial surveys. For these reasons rock sample data from Lusaka East were resubmitted to R-mode factor analysis. Ferric iron analyses available from spectrographic results from the Applied Geochemistry Research Group were available and included as the 11^{th} variable.

The associations extracted by the various factor models are shown in Table 37. The six factor model was chosen on the basis of a knowledge of element affinities with various minerals from Rankama and Sahama (1949). The minor-element associations were

Factor Model	3	% data correlation accounted for	4	% data correlation accounted for	5	% data correlation accounted for	6	% data correlation accounted for	7	% data correlation accounted for	8	% data correlation accounted for	9	% data correlation accounted for
Factors														
1	Cr 1.0 Ni .9 V .7 Ti .6 Fe_2O_3 .6 Cu .4 Mn .3 Co .3	31	Cr 1.0 Ni .8 V .7 Ti .6 Fe_2O_3 .5 Co .3	30	Ni .9 Cr .8 Fe_2O_3 .5 Mn .5 Ti .3	22	Ni .9 Cr .8 Fe_2O_3 .5 Mn .4 Ti .4	23	Ni 1.0 Cr .8	18	Ni 1.0 Cr .8	18	Ni 1.0 Cr .8	18
2	Ga .9 Pb .9 Mn .5 Ti .4 Fe_2O_3 .3	20	Pb .9 Ga .9 Mn .4 Ti .4 Fe_2O_3 .3	20	Pb .9 Ga .9 Mn .5	19	Pb .9 Ga .8 Mn .6	19	Pb 1.0 Ga .6	14	Pb .9 Ga .3	10	Pb .9	10
3	Zn .9 Co .7 Fe_2O_3 .4 Mn .4 Cu .4 V .3 Ti .3	22	Zn .9 Co .8 Fe_2O_3 .3 Mn .3 Ti .3 V .3	19	Zn .9 Co .7 Mn .4 Fe_2O_3 .4	19	Zn .9 Ti .3	12	Zn .9	10	Zn .9	10	Zn .9	10
4			Cu .9 Mn .3	11	Cu .9	10	Cu 1.0	10	Cu .9	10	Cu 1.0	10	Cu 1.0	10
5					V .7 Ti .6 Cr .4 Ga .4 Co .3	15	V .7 Ti .6 Ga .4 Cr .3	12	Ti .8 V .6 Ga .6 Fe_2O_3 .3 Cr .3	16	Mn .9 Fe_2O_3 .6	15	Mn .9	13
6							Co .9 V .4 Mn .4 Fe_2O_3 .3	13	Co .9 V .5	11	Co .9	9	Co .9	10
7									Mn .9 Fe_2O_3 .6	14	Ga .9 Ti .5	12	Ti .7 Fe_2O_3 .4	8
8											V .9 Ti .4 Fe_2O_3 .3	12	V .9	9
9													Ga .9	10
Total % data correlation accounted for		73		80		85		89		93		96		98

Table 37: Element associations, loadings and percentage data correlation accounted for by different factor models extracted from the Lusaka East rock data (169 samples).

related to various minerals as follows:-

(a) the Ni-Cr-Fe_2O_3-Mn association was related to mafic minerals such as amphiboles and pyroxenes,

(b) the Pb-Ga-Mn association was related to feldspars and epidote. Manganese is not a characteristic element of feldspar. With the data available, however, R-mode factor analysis is not able to make a perfect separation of association related to each mineral,

(c) the Zn-Ti association was related to biotite,

(d) the copper association could not be related to any specific mineral. It was noted in the previous section (6.3.3(v)), however that the majority of samples with a high copper content were taken from outcrops within the vicinity of known copper mineralisation. The copper association was, therefore, thought to reflect high background contents of copper in the general vicinity of copper mineralisation,

(e) the V-Ti-Ga-Cr association was related to the occurrence of muscovite in schists of sedimentary origin.

(f) the Co-V-Mn-Fe_2O_3 association was related to iron minerals such as hematite, magnetite or pyrite.

The R-scores of the rock samples for these six associations were then calculated. The mineral content of each rock sample was then postulated on the basis of significantly high R-score levels that it has in any of the associations. Significantly high R-scores were defined as 0.5. This arbitrary level of significant R-score was chosen simply to test the usefulness of the hypothesis described above (N.B. it would be more accurate, since the R-scores are normalised around a mean of zero and standard deviation measurements, to estimate the proportion of samples which incorporated a particular feature and use the equivalent R-score value which would include that proportion of samples above that value). For example, sample 9502 has a V-Ti-Ga-Cr R-score of 1.6 but low or negative R-scores in the other associations. It is, therefore, classified as a muscovite schist. Samples with low R-scores in all the associations were classified as quartzites because they included none of the above mentioned minerals. The epidote rich rocks were differentiated from feldspathic (granites) rocks by a Co-V-Mn-Fe_2O_3 R-score greater than 0.3 since magnetite or hematite were usually found to be in association with the epidote. Talc schists were assumed to be metamorphosed derivatives of amphibolites,or epidosites if they had a high Pb-Ga-Mn R-score. The mineral content of each rock sample has then been interpreted from the R-score values using the above criteria. The results have then been compared with mineralogy identified in the hand specimen in the field (Appendix 4). Using only this very crude classification the mineralogy of 71% of the samples have been correctly identified. Only 4% have been completely misinterpreted and the remaining 25% were interpreted partly correctly. That is to say that the presence of one or two of the minerals have been correctly interpreted from the R-scores. Four out of the 169 samples in the R-score calculation would not be classified correctly because their mineralogy was not represented by any of the factor associations, and were, therefore, omitted from these overall calculations.

Although the above results are far from perfect, they do indicate that factor associations might be more accurately interpreted in terms of mineralogy than rock type. Whether equivalent associations would be extracted from drainage sediment or soil sample data will depend largely on the nature of the secondary environment and the primary minerals. For example, the minor element content and subsequent factor associations extracted from data from clastic stream sediments formed entirely by mechanical erosion would give a close correspondence to those extracted from rock data in the same area, assuming negligible mechanical sorting Dambo sediments, on the other hand, have few if any of the primary minerals and, therefore, the relative proportions of the elements are likely to be changed in dambo sediments compared to their proportions in the underlying rocks. The different mobilities of the elements in such an environment must be taken into consideration.

Some idea of the rearrangement of the element proportions in the drainage sediments and soils in Lusaka East can be gained by comparing the factor associations from the rock, drainage sediment and soil sample data (Table 38). Manganese appears to be the element most affected in its element associations by changes in sampling media. Manganese occurs as a minor constituent in three associations extracted from the rock sample data but as a dominant element in a single association from both the drainage sediment and soil sample data. The concentration of manganese in drier stream sediments has already been shown to occur (section 6.3.3(iii)). Cobalt, on the other hand, only occurs in one association extracted from the rock sample data in which it is the dominant element in a Co-V-Mn-Fe_2O_3 association but is correlated strongly with the Ni-Cr dominated association, and to a much lesser extent with the copper and manganese dominated associations extracted from drainage sediment

Rocks		Drainage Sediment				Soils	
		(Initial samples)		(replicate samples)			
Element	Loading	Element	Loading	Element	Loading	Element	Loading
Ni Cr Fe_2O_3 Mn Ti	.9 .8 .5 .4 .4	Ni Cr Co Cu V Fe_2O_3	.9 .7 .7 .4 .4 .4	Ni Co Cr Zn V	.9 .8 .7 .5 .4	Cr Ni V	.9 .6 .4
Pb Ga Mn	.9 .8 .6	Pb Ga	1.0 .3	Ga Pb V	.8 .7 .5	Pb Ga	.9 .8
V Ti Cr Ga	.7 .6 .4 .4	Ti Cr	.8 .3	Ti Cr V	.9 .5 .3	Ti	.9
Cu	1.0	Cu V Ni Fe_2O_3 Co	.8 .7 .5 .5 .4	Cu V	.9 .3	Cu Co Zn V Ni Ga	.9 .8 .5 .5 .4 .3
Co V Mn Fe_2O_3	.9 .4 .4 .3	Mn Fe_2O_3 Co	.9 .4 .3	Mn Zn	.9 .4	Mn	.9
Zn Ti	.9 .3						
No. of samples	169	987		161		186	

Table 38: Comparison of minor-element associations extracted from the Lusaka East rock sample data by the six factor model with those extracted from the drainage and soil data by the five factor model.

data, and only with the copper dominated association from the soil sample data. The reasons for these changes are not fully understood but the affinities of nickel, cobalt and copper for hydrolyzate sediments is probably partially responsible for their association in the drainage and soil sediment media. Titanium and chromium have formed stronger more independent associations in the soil data than in the rock or drainage sediment data (Table 38). This is to be expected since both these elements will tend to be concentrated because of the resistate nature of ilmenite and chromite and the eluviation and leaching of the more mobile elements from the upper horizons of the soil profile.

6.5 CONCLUSIONS OF R-MODE FACTOR ANALYSIS ON GEOCHEMICAL DATA FROM KADOLA AND LUSAKA EAST

The minor element associations extracted by R-mode factor analysis from the minor element drainage sediment data from both Kadola and Lusaka East have mostly been shown to be related to geological features.

The R-score distribution of each factor association was found to be a useful method of classifying the features controlling the minor element content of each sample, and has indicated the presence of rock units in areas where they were not previously known to exist, because of lack of outcrop.

The minor element associations extracted from the data of the two areas are very similar in most cases, and have been related to similar lithologies in both areas (Table 39).

A comparison of minor element association R-scores of the Lusaka East rock data with the mineralogy of the rock samples

Factor associations from		Features to which associations have been related and remarks
Kadola	Lusaka East	
Ti V Cr Ni Ga Co	Ti Ga Cr Cu V	Schistose units of argillaceous origin. In both Kadola and Lusaka East high R-scores in these associations indicated areas underlain by schistose rocks which had not previously been recognised. In Kadola this simple explanation was complicated by the secondary enrichment of ilmenite in the sediments overlying a carbonate facies containing ilmenite.
Pb Ga	Pb Ga	Granitic rocks in both areas. High Pb-Ga R-scores in conjunction with associations indicating other rock types might indicate the presence of lead mineralisation.
Mn Fe_2O_3	Mn Fe_2O_3 Co V	Carbonate or basic rocks due to the secondary concentration of manganese and iron. This concentration is the result of the raised pH and resultant oxidation of these elements to insoluble oxides in sediments overlying these rock types.
Cu Ni Cr Co	Ni Cr Co Cu V Fe_2O_3	Basic rocks. Basic rocks were not previously known to occur in Kadola. The high copper loading in the association from the Kadola data was taken to indicate possible copper mineralisation in association with the basic rocks which was later found to be the case. High R-scores in certain areas in both Kadola and Lusaka East indicated the presence of underlying basic rocks where they had not previously been mapped.
Fe_2O_3 Co Ni V Ga		Thought to reflect iron laterite occurrences. Unrelated to any geologic feature.

Table 39: Comparison of factor associations extracted from drainage sediment data from Kadola and Lusaka East and the features to which they have been related

indicated that the factor associations might be more accurately interpreted in terms of the minerals present than the more general gross rock type.

R-mode factor analysis will probably not extract an association reflecting mineralisation unless there are a fair number of samples, probably between 10% to 20%,which have their minor element content affected by mineralisation. R-mode factor analysis cannot, therefore, be used for finding mineralisation directly but as an aid in evaluating the geologic units influencing the minor element content it would be a useful technique.

CHAPTER 7

DISCUSSION OF RESULTS

7.1 INTRODUCTION

The subjects discussed in the previous two chapters can be divided essentially under two headings. One section considers the viability of broad scale drainage sediment sampling as a means of obtaining knowledge of the primary geochemistry and in particular as a means of defining metallogenic provinces using a moving-average smoothing technique. The other section considered the use of R-mode factor analysis as a means of interpreting the features controlling multi-element geochemical data, and R-scores as a means of indicating the provenance of these features.

In this chapter the factor analysis results of the broad scale provincial sampling are discussed in relation to those from the regional areas, which have a denser drainage sediment sampling cover, in order to substantiate the use of broad scale sampling. The implications of the similarities and differences of the minor-element associations extracted from the sets of data from the three different areas are also discussed. In addition, some of the theoretical limitations concerning the use of R-mode techniques are discussed.

7.2 DISCUSSION OF BROAD SCALE PROVINCIAL SAMPLING

In chapter 5 the minor-element distributions resulting from the low density provincial sampling were shown to be related to the broad scale primary features. Most of the minor-element associations extracted by R-mode factor analysis were also related to primary features and their R-score patterns were shown to define the general braod scale distribution of these features (section 5.3.2). The main associations extracted from the provincial data are similar to those extracted from the Lusaka East data covered at a sampling density of 1 sample every 2 square miles, and from the Kadola data at a sampling density of 1 sample every 4 square miles (Table 41). This similarity in associations from three sets of data sampled on three different scales is additional evidence indicating that almost any drainage sediment sample density up to 1 sample every 75 square miles is capable of indicating the main controlling features of geochemical drainage sediment data in secondary environmental conditions such as exist in Zambia. The sample density, therefore, need only be governed by the size of the features to be measured, their structural orientation and the accuracy with which their boundaries are to be located.

Recent work in Uganda has confirmed this conclusion (Reedman and Gould, 1970). Moving average results of Co, Cu and Zn data selected on the basis of 1 sample every 0.7 square mile mile compared with those from data at 1 sample every 70 square miles over the same 7000 square mile area gave very similar results. The high Co, Cu areas tended to correspond to areas of basic gneiss, and areas of high Zn, and to a lesser extent Cu, tended to correspond to areas of graphitic gneiss.

The main practical justification for low density drainage sediment sampling is firstly on the speed and low cost with which the samples can be collected and analysed, secondly the ability of the geochemical results to: (a) define possible tin and copper metallogenic districts or provinces and probably geochemical provinces of other elements, and (b) from R-mode factor analytical associations and R-scores to indicate the main controlling lithologies and their geographical distribution.

The original 1,100 samples from the 80,000 square mile area took only 90 sampling days to collect. The main limitation was being restricted to drainages which were crossed by or ran near to the roads. Since the roads frequently followed catchment divides, and only occasionally crossed the drainages, their use was often a severe limitation to maintaining an even sample density. If a helicopter sampling programme was adopted not only could the sampling be carried out in a shorter time, but also they could be collected on a very regular interval. A regular interval of sampling would greatly increase sampling representivity of the survey.

Assuming a working range of about 200 miles a helicopter could cover an area with a radius of about 100 miles from a base camp. An area of 80,000 square miles could be covered from 2 to 3 base camps. Assuming a sampling grid of approximately 1 sample every 10 miles, a sample pick up time of 5 minutes and a helicopter speed of about 60 mph it would require about 15 minutes per sample. Therefore, 32 samples could be collected in an 8 hour working day, and 25 days to collect 800 samples. These are, of course, only approximate figures and would have to be greatly varied depending on the conditions and the flying abilities of available helicopters. On the flat Zambian plateau where the dambos are open and clear of trees this sampling rate could probably be maintained. In the escarpment areas, however, where the valleys are often deeply incised, access by helicopter would be more difficult and sampling time greatly increased. The main advantage of using a helicopter, however, is firstly in areas of poor access and secondly as a method of gaining a good sampling distribution, which would result firstly in greater sampling representivity and secondly greatly facilitate statistical analytical handling of the data.

7.2.1 Provincial geochemical sampling procedures

An attempt was made to evaluate the influence of the pH and catchment size on the geochemistry of the samples.

The pH was found on average to vary very little and was usually within the 6-7 pH range except in streams draining carbonate and basic rocks where it increased to the 7-8 pH range. Clearly the pH is controlled by the underlying lithology. Differences in minor-element composition in the drainage sediment due to differences in pH will, therefore, be indirectly due to the underlying lithology. Since it is the differences in minor-element composition reflecting the underlying geology which is of interest the differences in pH are of little practical significance to provincial sampling in environments such as occur in central Zambia.

The influence of the catchment size on the minor-element content of drainage sediment was found in practice extremely difficult to assess. Garrett (1966) showed that the Cr, Mn, Ni and Pb content of sediment from drainages of 5-7 sq miles in catchment were closer in value, than those from sediment of major drainages, into which the smaller streams drained, to those from reconnaissance sample sites from streams of less than 5 sq mile catchments. He concluded from this that the stream sediment from catchments with 5-7 sq miles gave a better picture of the primary geochemistry than stream sediment derived from larger catchment areas. This method of evaluating the influence of catchment size on the geochemical content of stream sediment neglects both the affect of catchment size on other elements, and the influence which the addition of colluvial material near the sample site on a large stream will have on its minor-element content.

Garrett's evidence implies that there is some overall correlation of minor-element content of stream sediment with the size of the drainage catchment from which the sample has been taken. To check this hypothesis the intercorrelation of the elements (Co, Cr, Cu, Ga, Fe_2O_3, Mn, Ni, Pb, Sn, Sr, Ti, V, Zn) with the catchment size was calculated from the 271 samples with catchments greater than 10 sq miles. None of the correlations were greater than +0.048 or less than -0.073 which are not significant at the 90% probability level. This shows that catchment size alone is not a major influence of the minor-element content of drainage sediment.

From field observations in central Zambia it was noted that where a major stream was incised to bedrock most of its sediment is derived from the bedrock immediately adjacent and/or just upstream from a sample site. In such a situation catchment size will have little, if any, chance to modify the minor-element content of the sediment. This aspect is demonstrated by the minor-element content of a sample, taken from a major drainage (159 sq miles) at a point where it ran through outcrops of epidosites and basic rocks. The minor-element contents of this sample are much closer to the mean minor-element values of 5 samples taken from small drainages (below 2 sq miles) than to the mean minor-element values of the 69 within the upstream catchment area (table 40(a)). Most of the catchment area is underlain by schist, granite gneiss and quartzite. Where a major drainage is not incised to bedrock the minor-element content is not so clearly related to the bedrock at the sample site. For example some of the minor element values of a sample from a major drainage (122 sq miles) at a point where it was underlain by the Lower Roan formation, are closer to the mean minor-element values of five samples

elements	Minor-element contents of sediment from		
	major drainage (159 sq.mi.)	minor drainage on same geol. as major drainage sample.	minor drainage within catchment area of major drainage.
Co	60	40*	20*
Cr	200	150	70
Cu	200	60	12
Ga	40	12	11
Fe_2O_3	17%	9%	5%
Mn	1,600	1,000	500
Ni	85	50	20
Pb	40	11	14
Ti	11,000	9,000	6,000
V	400	300	100
Zn	200	60	50
No. of samples	1	5	69

(a)

elements	major drainage (122 sq.mi.)	minor drainages on same geol. as major drainage sample.	minor drainages within catchment area of major drainage
Co	30	13*	20*
Cr	20	11	25
Cu	16	13	13
Ga	4	5	8
Fe_2O_3	1.2%	1.3%	1.5%
Mn	60	30	70
Ni	20	30	50
Pb	30	4	4
Ti	1,600	2,800	3,000
V	40	20	55
Zn	40	45	40
No. of samples	1	5	35

*Geometric mean in ppm

(b)

Table 40. Comparison of minor-element content of sediment from major and minor drainages.

taken on the same geology and some to the mean of the minor-element values of 35 samples within the catchment area (table 40 (b)). The catchment area was underlain by Lower Roan, undifferentiated Basement units and calcareous units. The differences in the mean minor-element values shown in Table 40 (b) are in any case too low to come to a definite conclusion. Data of samples from other major drainages gave similarly inconclusive results. There was also no pattern in the elements which tended to be higher or lower in the major drainages suggesting a progressive elutriation or concentration of particular elements.

It must be concluded that the behaviour of the minor-elements in sediment from large catchment areas, and the extent to which the minor-element content of this sediment reflects the primary geochemistry of the upstream catchment area remains problematic. The above evidence indicates, however, that the proportion of colluvial to alluvial material which is included in the sediment is a more important feature controlling the minor-element content of sediment from large drainages than catchment size alone. Although every situation will have to be evaluated on its own merits it is probably best to sample drainages with relatively small catchments. This is suggested on the assumption that it is preferable firstly, to avoid, as far as possible, mixing of sediments from different geologies so that their minor-element contents will more likely reflect the true primary geochemistry, and secondly so as to avoid possible differences due to secondary environmental features which are as yet unrecognised.

7.3 DISCUSSION OF FACTOR ANALYSIS

7.3.1 Comparison of associations extracted by R-mode factor analysis from the drainage sediment data from the three areas

The minor-element associations extracted from the drainage sediment data from the three areas by R-mode factor analysis are very similar. Associations which closely resemble one another have been shown in previous chapters (5.3.2, 6.2.5, 6.3.3) to be related to the same lithologic types or secondary features in each area (Table 41). In each of the areas the associations dominated by titanium and invariably including V-Ga-Cr have been related to argillaceous rocks and the metamorphic schists derived from them. The associations invariably including Ni-Co-Cr have been related to basic rocks in each area. The Pb-Ga associations which are identical in the factor solutions from each of the sets of data have been related to granites and granitic gneisses. The Mn-Fe_2O_3 associations have been related to the secondary enrichment of these elements over carbonate and basic rocks, and in drier drainage sediments. The Cu-Ga association extracted from the Provincial data and the Fe_2O_3-Co-Ni-V-Ga association extracted from the Kadola data are not reflected in the factor solutions from the sets of data from the other areas. A possible exception is a Ga-Cu-V association, with element loadings of 0.8, 0.5 and 0.4 respectively, extracted as a fifth factor of the five factor model from the Lusaka East data, which might reflect a similar control as the Cu-Ga association extracted from the Provincial data (see Table 29). The former association, however, has not been interpreted and the primary feature controlling the latter is not clearly understood although the high R-scores corresponded to copper metallogenic areas. Zinc, tin and strontium were not included in the Kadola, Lusaka East factor analysis data.

In each area the associations extracted by R-mode factor analysis from the drainage sediment data are always more similar to the associations extracted from the bedrocks than they are from the

Provincial			Kadola			Lusaka East		
Element	Loading	% correlation accounted for*	Element	Loading	% correlation accounted for*	Element	Loading	% correlation accounted for*
Ti Cr V Ga Fe_2O_3	.8 .6 .6 .6 .4	18	Ti V Cr Ni Ga Co	.9 .6 .6 .5 .4 .3	27	Ti Ga Cr Cu V	.8 .4 .3 .3 .3	15
Pb Ga	1.0 .5	9	Pb Ga	.9 .6	13	Pb Ga	.9 .6	14
Co Ni Cr	.8 .8 .4	16	Cu Ni Cr Co	.9 .4 .4 .3	16	Ni Cr Co Cu V Fe_2O_3	.9 .8 .7 .5 .4 .4	31
Mn Fe_2O_3 V	.9 .6 .3	14	Mn Fe_2O_3	.9 .3	11	Mn Fe_2O_3 Co V	.9 .6 .4 .4	21
Sn	1.0	8						
Sr	1.0	8						
Zn	.9	8						
Cu Ga	.8 .3	7	Fe_2O_3 Co Ni V Ga	.8 .6 .3 .3 .3	18			
Total % inter-element correlation accounted for		88			85			81

*% of inter-element correlation accounted for by each factor.

Table 41: Equivalent minor-element associations extracted from the drainage sediment data from the three areas

soils (Tables 18, 24, 32). Assuming that the associations extracted from the rock sample data are representative of the element affiliations of the regional primary features, this evidence indicates that the composition of the drainage sediment, as it occurs in Zambia, is more similar to the minor-element geochemistry of the rocks, than is that of the upper horizon of the soils. This fact reflects the greater extent of differentiation due to eluviation and leaching which the upper horizons of the soils have undergone compared to drainage sediments. The drainage sediments, on the other hand, are always having primary minor-element content renewed whether they are sandy sedimants in the escarpment areas or dambo sediments on the plateau. That is to say, the primary element associations are not greatly disturbed in the sandy stream sediments because rock fragments are continuously being eroded and added to the stream sediments. Excessive elutriation of the elements from the small streams is minimised by their dryness for most of the year and the resultant lack of chemical weathering or transporting media. In dambos, despite most of the primary minerals having been chemically broken down, and most of the minor elements being held in ionic form in their acid environment, the primary element associations will be largely maintained, firstly by element absorption onto clay and organic material, and secondly by their replenishment by groundwater which is charged with ions from the underlying weathered bedrock. Of the elements, which have been analysed, manganese and iron are exceptions to this general rule. Both these elements tend to be concentrated in the drainage sediments and soils in comparison to rocks by their precipitation as insoluble hydroxides.

The recurrence of similar associations in different sets of data from various areas, their proved relationships to the same primary and secondary features,and the fact that the associations extracted from the drainage sediment are closer to those extracted from the rock data than those from the soil data, lead to two important conclusions. Firstly that R-mode factor analysis of drainage sediment data will extract associations of elements which reflect the features controlling their distribution assuming that the same secondary conditions as occur in the field area. From this base the method could be extended to defining other primary features besides schists, granites and basic rocks by using elements which are characteristic of other lithologies. Secondly drainage sediment from small drainages is a better sampling medium than either soils or rocks for gaining a knowledge of the primary distribution of the elements and the features controlling them. This is becuase firstly the soils have undergone a greater differentiation due to leaching and elutriation than drainage sediments and secondly rock sampling is difficult and tends to be unrepresentative in areas of poor outcrop, and deep weathering.

7.3.2 Some considerations of the theoretical assumptions necessary for the application of R-mode factor analysis

It might appear from the previous section, and it is a commonly held misconception, that R-mode factor analysis applied to geochemical data will extract minor-element associations which are guaranteed to reflect the controlling features of the minor-element distributions such as lithology or secondary environmental influences. This is, in fact, not so because of the limitations of the correlation coefficients from which the factor associations are extracted.

The majority of the data reduction from the data matrix to the factor matrix takes place when the correlation coefficient matrix is calculated. It will be shown in the following examples that it is at this stage that most information is lost, and/or error introduced because the correlation coefficients used only measure the overall correlation between each pair of elements and does not discriminate between sample clusters from different controlling features (populations). The Pearson product moment correlation coefficient used in this study measures the linear correlation between the variables. The strength of a linear relationship corresponds to the degree to which the variation of one variable is associated with proportionate variation of the other variable. The values of variables from geochemical data, however, will theoretically tend to form clusters, rather than be linearly related, with each cluster formed by a distinct population (e.g. lithology). A simple example, taking analyses of three variables, nickel, manganese and lead, from samples of two rock types, granites and basic rocks, will illustrate this point. In three dimensional space with three orthogonal axes representing the three variables there will be two clusters of points (Fig. 55(a)). One cluster of points will represent basic rock samples with high nickel and manganese and low lead values, and the second cluster of points will represent the granite samples with high lead and low nickel and manganese values. The correlation coefficients calculated from this data would show a strong positive correlation of Ni-Mn and a strong negative correlation of Pb-Mn and Pb-Ni. Factor analysis of these correlations would correctly indicate two factors,one reflected by a Ni-Mn association and a second by Pb. This example indicates that despite a non-linear relationship of the variables, R-mode factor analysis will under certain conditions give correct minor-element associations. By minor-element associations, it is meant that they show the true affinities of the minor-elements which

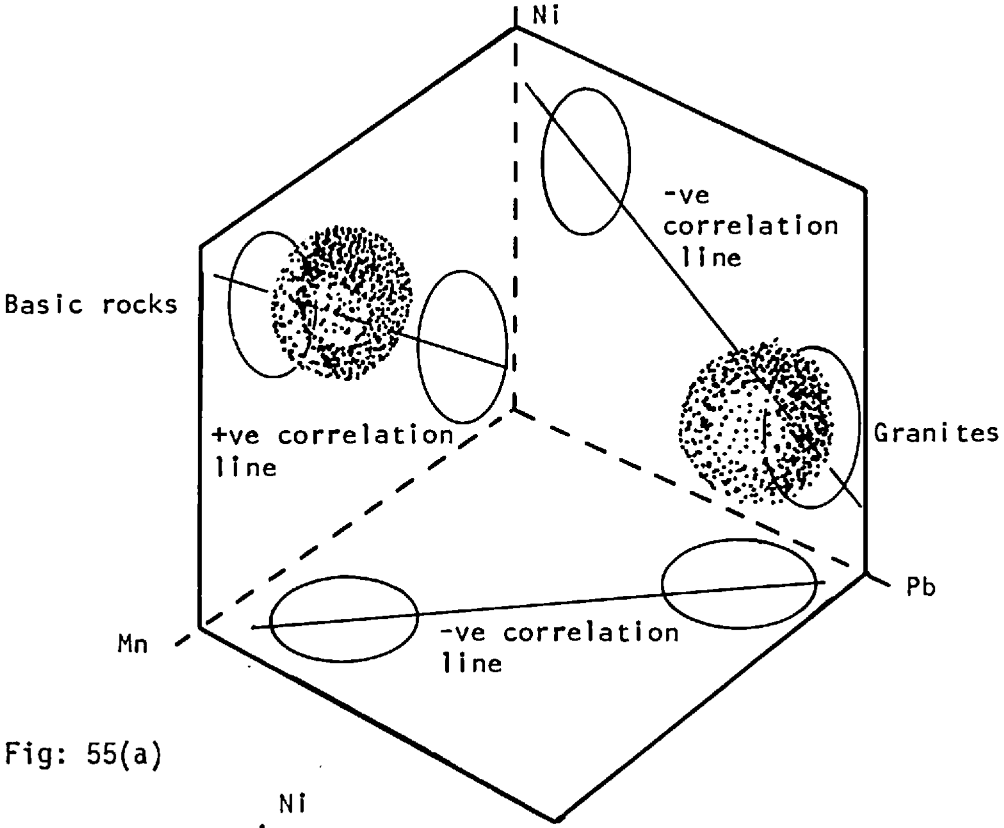

Fig: 55(a)

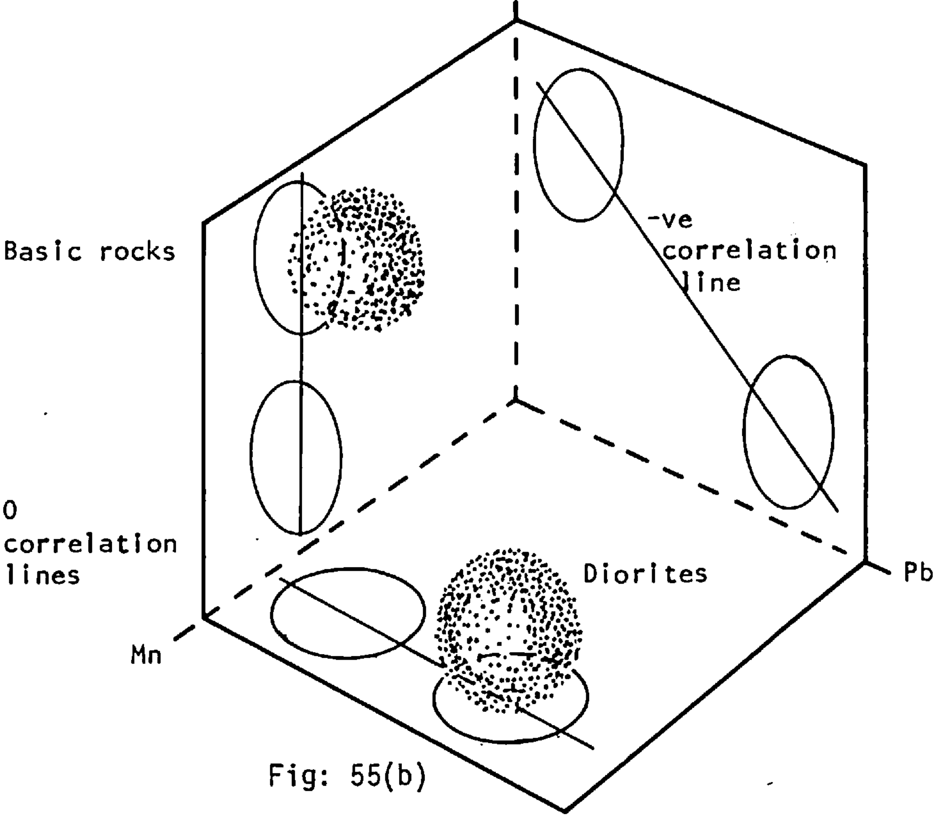

Fig: 55(b)

Fig: 55 3-dimensional plots of hypothetical data distributions of 3 elements from two different lithologies correctly reflect the controlling features (e.g. lithologies).

Rather different affinities are revealed, however, if diorites had been sampled instead of granites because the manganese content is, on average, a little over 1000 ppm in both diorites and basic rocks. In a three dimensional diagram there will still be two clusters, one derived from basic rocks with high nickel and manganese and another derived from the diorites with high lead and manganese (Fig. 55(b)). The correlation between Ni-Pb will still be strongly negative but those between Mn-Ni and Mn-Pb will tend to zero because of the low variance in the manganese values. Factor analysis of these correlation **coefficients** would still extract two strong antipathetic factors, one dominated by nickel which would reflect basic rocks and the other dominated by lead which would reflect the diorites. Manganese would not be related strongly to either of these factors simply because no lithology with low manganese content had been sampled. This illustrates the important point that in the R-mode factor analysis of data from mixed rock populations the pairs of variables must occur at different concentration levels in at least two lithologies before a significant correlation between any given pair is revealed.

If a third population of data taken from quartzites, with low manganese, nickel and lead values, are added to the data in the last example, these simple relationships are further complicated (Fig. 56(a)). In this case there would be low manganese values which should result in positive correlations of both Ni-Mn and Pb-Mn. If the two dimensional plots of the elements one against the other are looked at separately, it will be seen that there is a cluster of points at each of three corners (Fig. 56(b)). The strong negative Ni-Pb correlation apparent in the previous example will now be

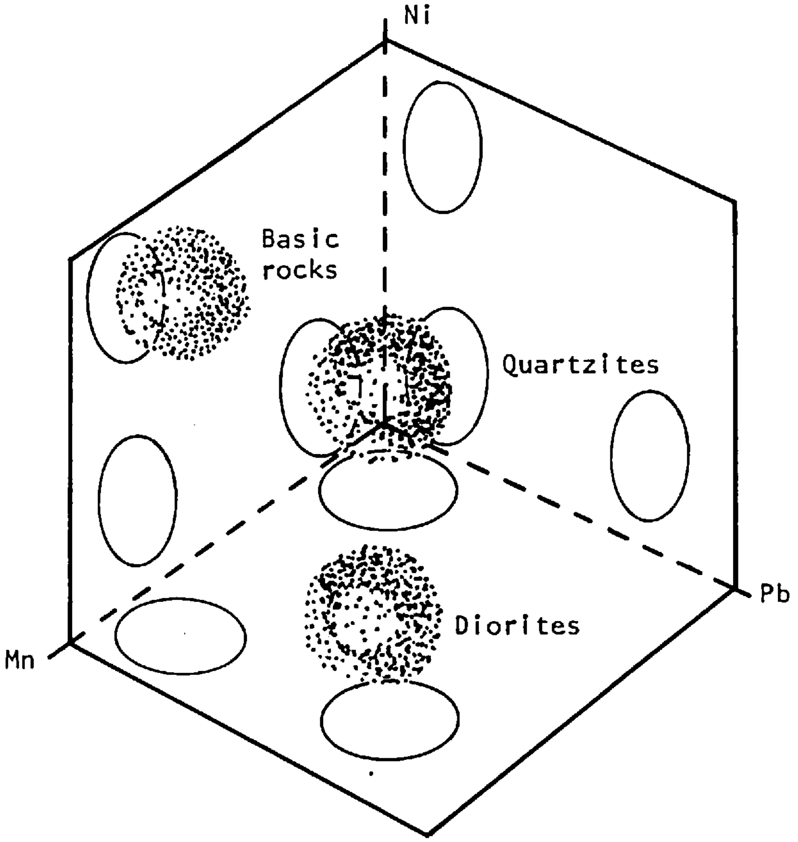

Fig: 56(a) 3-dimensional plots of hypothetical data distributions of 3 elements from three different lithologies

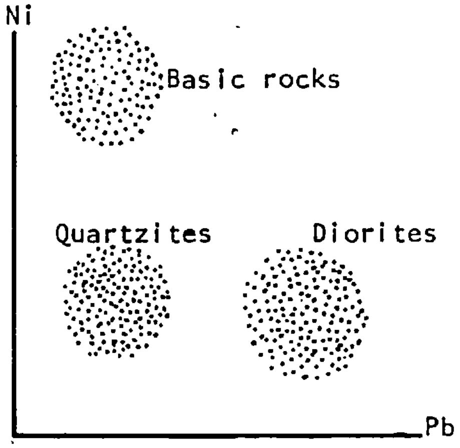

Fig: 56(b) 2-dimensional plots of hypothetical distributions of 2 elements from three different lithologies reduced by the break in linearity of the clusters caused by the introduction of quartzite data. The value of the correlations in this example, and the ability of factor analysis to show distinct Ni-Mn and Pb-Mn associations reflecting basic rocks and granites respectively, will depend, in this case, on the proportion of samples in each group (cluster) of data and their relative dispositions. This example illustrates the point that the correlation coefficients only measure the overall correlation, and R-mode factor analysis can, therefore, only extract element associations which reflect the overall trends indicated by the correlation coefficients. There is no guarantee that the extracted associations will exactly reflect the lithologies. It is fortunate if, as in this example, various associations are obtained which typify the rock types present but very probably it will not obtain all associations characteristic of each lithology. In this example no amount of manipulation is going to reveal an association of elements reflecting the quartzite population. For a lithology or controlling feature to be reflected by a characteristic association of elements, the overall trend of a correlation coefficient of at least one pair of elements must be typical of that lithology.

The correlation coefficients are not being used theoretically correctly in this situation if the aim is to extract associations of elements all of which are guaranteed to be characteristic of particular lithologies (controlling features). Assuming that geochemical data derived from a number of different rock types form clusters in multi-variate space with each cluster corresponding to one of the lithologies, it is apparent that a multi-variate technique would be required to locate these clusters in order to define the true element characteristics of the sampled lithologies.

The problem with this approach would be that geochemical data in most situations does not cluster to the same extent as those in the theoretical examples shown above. For example, when nickel and lead values from basic and granite rock samples from Lusaka East are plotted against each other, the two groups of samples could not be separated from this plot alone, if their composition were not already known (Fig. 57). The linear spread of values is due to: (a) real variation in rock composition, and (b) sampling and analytical errors. This spread of values between clusters would be increased, if the geochemical data was derived from drainage sediment samples, because of the mixing of drainage sediment from different sources upstream from the sample point.

Apart from the greater spread of the clusters of values and their non-spherical shape, the nickel, lead plot (Fig. 57) indicates a negative correlation coefficient between these two elements as was postulated in the theoretical example (Fig. 55(a)). Similarly, when the nickel, lead values from all the rock samples from Lusaka East are added to this plot, it can be seen that this simple relationship between two populations is confused (Fig. 58) as was indicated by adding data from a third population in the theoretical example illustrated in Figs. 56(a) and (b). The general inverse relationship of nickel to lead reflecting the granite and basic rock compositions, however, is not obliterated, and this is reflected in a correlation coefficient of -0.307, which is statistically significant at the 99% probability level for the 177 samples included. This correlation coefficient could have been reduced to zero or even made positive if a large number of epidosite samples had been included. Epidosites have been shown earlier (see section 6.3.3, Table 33) to have both relatively high lead and nickel

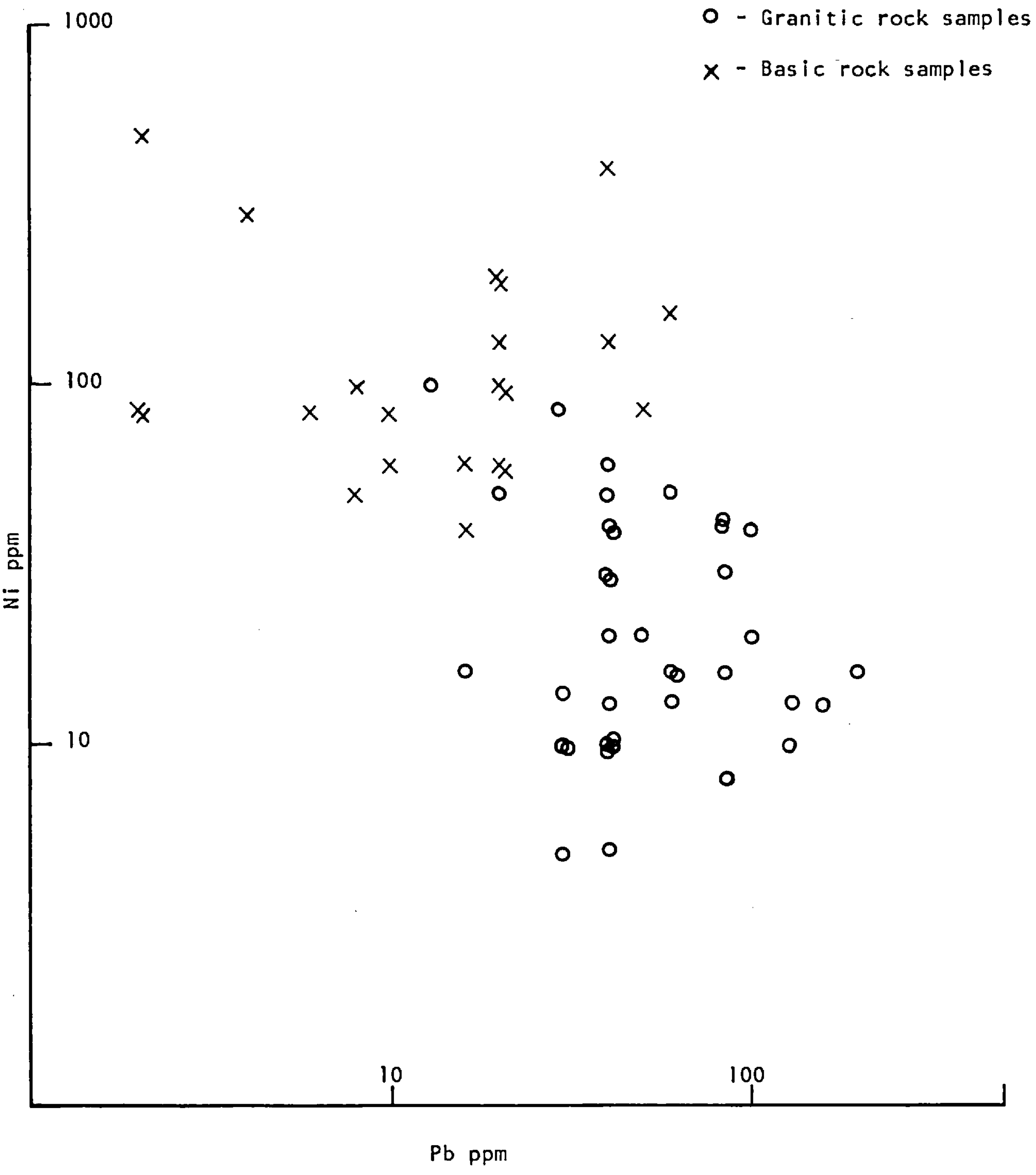

Fig: 57 Plot of nickel and lead data from granitic and basic rock samples from Lusaka East

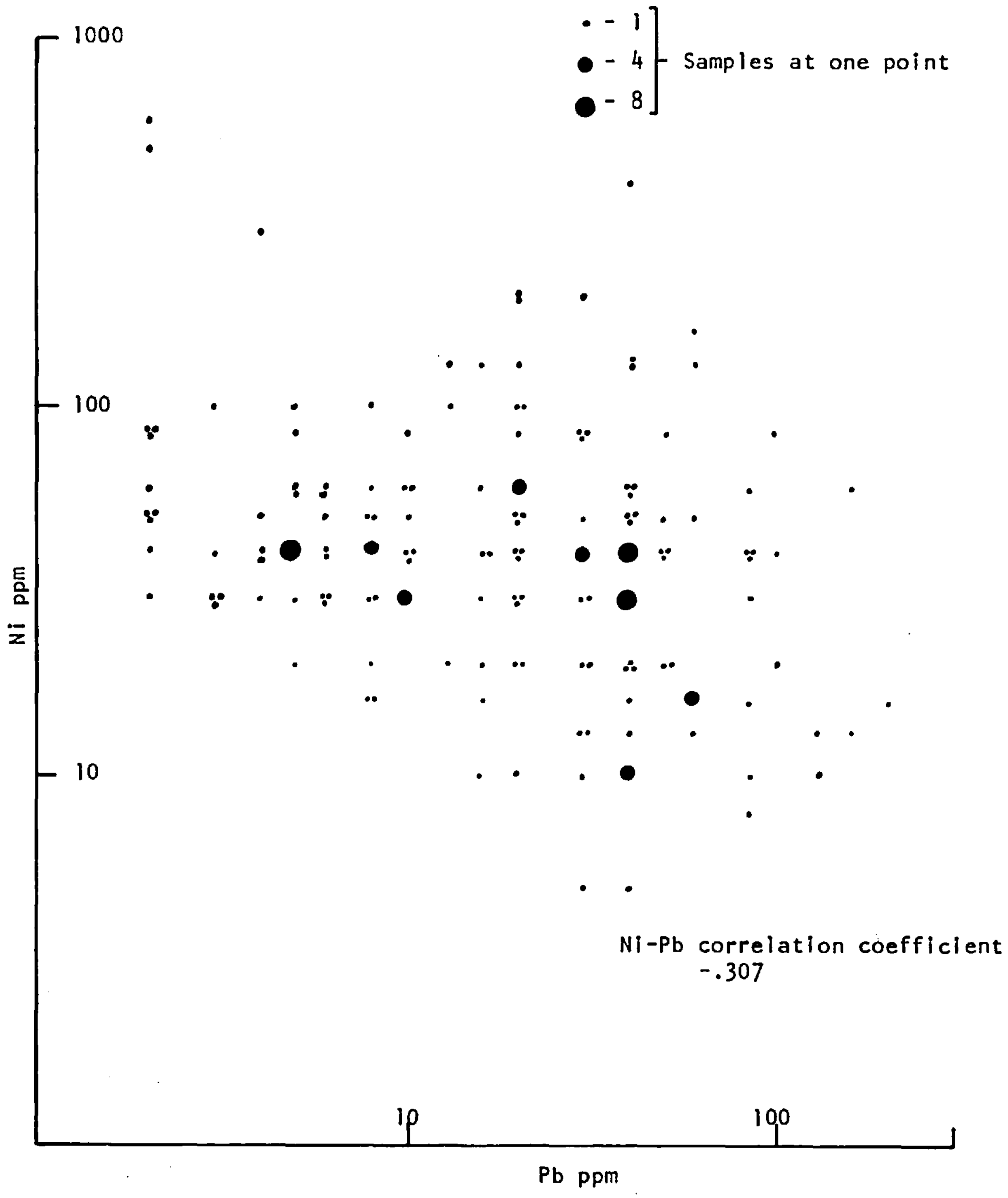

Fig: 58 Plot of all Ni-Pb data from Lusaka East rock samples values. If these values were plotted with quartzite samples with low lead and nickel values, there would probably be a positive nickel and lead correlation.

In conclusion, therefore, if R-mode factor analysis is used to extract minor-element associations from multi-element geochemical data which are characteristic of the controlling features (e.g. lithologies), it must be kept in mind that the extracted associations will depend on the overall correlation coefficients between each pair of variables. The overall correlation coefficient will in turn depend on:

(a) the controlling features (e.g. lithologies) which have been sampled,

(b) the proportion of samples derived from each controlling feature,

(c) the relative disposition of the clusters of sample values due to the various controlling features between each pair of variables. This point will include differences in element values resulting from the different lithologies.

It is probably impossible to unravel these influences on the ultimate value of a correlation coefficient which reflects only the overall trend shown by the mixed lithologies. Until, however, some better multi-variate technique is devised, which can handle a large amount of multi-variate data, R-mode factor analysis remains the only feasible technique for deducing the minor-element associations from multi-element geochemical data. Providing elements characteristic of the main lithologies are included in the data, and the qualifications discussed above are kept in mind so that geochemically nonsensical associations are not considered, the minor-element associations extracted should reflect the main geological and secondary environmental features.

7.3.3 A limitation of the R-score method of measurement

R-scores have been shown to be a useful way of indicating the provenance of the features controlling the geochemical data in the previous two chapters. The main weakness, however, is in their method of calculation which does not take enough into account the inter-element proportions, as they are indicated by the element loadings. For example, R-scores of a Cu-Ni-Cr-Co association, extracted from the Kadola drainage sediment data cannot differentiate between samples with high copper values only, and those with values in all the elements in proportion to those indicated by the loadings (section 6.2.5 (iv)). This limitation could result in the non-recognition of sample values derived from mineralisation. Or it could result in other sources not reflected in any of the extracted associations, and must be kept in mind when interpreting the distribution of R-score patterns.

CHAPTER 8

SUMMARY AND CONCLUSIONS AND FUTURE WORK

8.1 SUMMARY AND CONCLUSIONS

8.1.1 Provincial sampling over central Zambia

The aim of the provincial (wide interval) drainage sediment sampling survey was to determine if the geochemical data from these samples could define metallogenic provinces in conditions of mixed bedrock geology, mineralisation and secondary environment as they occur over 80,000 sq. mi. of Precambrian Basement and Katangan rocks in central Zambia.

(i) Provincial reconnaissance field sampling techniques

Drainage sediment samples were taken at a nominal density of 1 sample every 50-100 sq. mi. The samples were taken mostly from drainages of less than 10 sq. mi. catchment but they were also taken from drainages over 10 sq. mi. in order to determine the affect of catchment on the minor-element content of the drainage sediment and their ability to reflect the primary geochemistry.

The evidence indicated that there was no overall correlation of minor-element content with catchment area. From limited studies it appears that the minor-element content of the drainage sediment is not so much related to catchment size as to the proportion of colluvial to alluvial material which composes the drainage sediment (see section 7.2.1). It was concluded that the sampling of small catchments was preferable, firstly so as to avoid, as far as possible, the mixing of sediments from different sources, so that their minor-element content might reflect more exactly the geochemistry of particular geologic influences, and secondly, so as to avoid any secondary influences due to large catchments which have not yet been recognised.

Drainage sediment type from the central Zambian plateau was found to be a remarkably constant grey sandy clay type similar to the G_1 horizon of the hydromorphic dambo soils (see section 4.2.1). In the escarpment areas stream sediments were a silty sand. Both these sediment types yielded enough -80 mesh fraction for analysis. Most of the minor-elements tended to be slightly depleted in silty sand stream sediments compared to the dambo type plateau drainage sediments. The differences were not large enough to form regional patterns of their own or influence the main primary regional patterns, with the possible exception of nickel (see section 5.1.5). Manganese, ferric iron and titanium were found to be slightly enhanced in value in the sandy stream sediment compared to the dambo type grey clay sediments (see section 6.3.3). The uniformity of sample type from the plateau drainages at least helped to reduce other possible variations of minor-element content due to secondary conditions.

Other conclusions and observations as to sample technique and secondary conditions are as follows:

(a) Variations in pH of the drainage sediment were found to be small (6-8 pH range) and controlled by lithology. The pH was, therefore, eliminated as a possible feature controlling the minor-element distribution (see section 7.2.1).

(b) The collection of drainage sediment samples from drainages crossed by motorable roads gave good sample coverage where road and sample density was high. Where these were low and where the roads tended to follow the catchment divides, sample coverage tended to be poor and difficult to maintain (see section 4.2.1).

(c) The combined sampling and analytical precision of the drainage sediments was an overall average of 79% for all the elements at the 95% confidence level (see section 4.4.7.)

(ii) Data handling

(a) The use of computer cards was found to be a useful method of data handling. When each card includes the data from an individual sample, the sorting and re-arranging of samples into different categories, for the application of computerised techniques, was greatly simplified (see section 4.5.1).

(b) The calculation of means, and basic statistical parameters, and the plotting of histograms was greatly facilitated by computerised techniques (see section 4.5.2).

(c) The use of the automatic CALCOMP plotter reduced the drudgery and man hours required for plotting of data. Its main limitation was in the number points that it could plot at one time, which was from 1000 to 2000 depending on the size of the map (see section 4.5.3).

(d) Moving average analysis was found to be a satisfactory technique for smoothing of the single element data, permitting contouring of the results. It was concluded to be a useful technique for elucidating the broad scale minor-element patterns of the provincial data (see sections 4.5.4 and 5.1.1).

(iii) Relationship of minor-element patterns from the provincial reconnaissance to the metallogenic provinces

The variations of the data from provincial geochemical drainage sediment samples defined, with higher background values, some of the metallogenic provinces and districts shown in fig. 3 as follows:

(a) An area with higher tin background corresponded to the Choma tin belt (district). The enhanced tin content of the drainage sediment in the area was shown to result from an increase in the tin content of the country rocks (see section 5.3.1).

(b) Areas with high copper background corresponded to the Copperbelt metallogenic province, and the Lusaka East-Mumbwa copper metallogenic province. The enhanced background value in the Copperbelt could not be shown definitely to be the result of higher copper content in all the surrounding bedrock units because of the difficulty of obtaining representative fresh rock samples due to the lack of outcrop. It was, therefore, concluded that the increased copper background in the drainage sediment was due to the higher copper content of the bedrock and/or to the increase of minor mineralisation. In Lusaka East copper metallogenic province fresh rock samples were easier to collect but they did not show an increased copper content. The enhanced copper background in the drainage sediment was related, therefore, to the increased incidence of minor mineralisation.

The relationship of enhanced copper background to the Broken Hill-Mwinilunga metallogenic belt could not be established because of lack of access which might permit a reasonable sample coverage. In addition, the high copper background coincided with enhanced cobalt, chromium, nickel, vanadium and ferric iron background patterns which suggested that underlying basic rocks were present (see section 5.1.3(i)).

(c) In the Feira carbonatite area strontium was found to have enhanced background values in the drainage sediment. Strontium, however, was also enhanced in value in sediment draining calcareous rocks in general. It was concluded that provincial sampling would be an adequate method for defining carbonatite areas providing other characteristic elements were determined in addition to strontium. Phosphorous, barium,yttrium, lanthanum, cerium and niobium have been suggested as additional possible tracers for carbonatites (Deans and Powell, 1968) (see section 5.1.3(iii)).

(d) The lead-zinc mineralisation at Broken Hill was not detected by enhanced lead and zinc values in the drainage sediment of the provincial samples. This was because of the low drainage density in the area, and because the few dambos that were in the area were contaminated by mining activity. Because of the lack of any larger regional lead or zinc background pattern in the area it was concluded that the mineralisation was possibly of limited occurrence and, therefore, does not merit definition as a metallogenic district (see section 5.1.3(iv)).

(iv) Relationship of minor-element patterns from provincial reconnaissance to lithology

It was noted that most of the element contents in the drainage sediment were influenced to a greater or lesser degree by the different lithologies (section 5.1.4). The single element distributions noted to reflect the lithologies are as follows:

(a) All the elements with the exception of lead and tin are greatly enhanced in value in the stream sediments over the Karroo basalts around Livingstone.

(b) The areas of high zinc background corresponded to the main incidence of the Basement units. It was suggested but not shown conclusively that this relationship was due to the increased occurrence of biotite schists in the Basement since biotite tends to hold a greater amount of zinc.

It was not possible to relate the variations in background value of any of the elements to other lithologies because of the scale and degree of smoothing of the moving-average analysis.

(v) Relationship of minor-element patterns from provincial reconnaissance to the secondary environment

Manganese and to a lesser extent ferric iron was found to be enhanced in the drainages of the southern half of the country compared to the north. Because the distribution of manganese was found to be enhanced in the same way in the soils but not in the rocks, and because it reflected the rainfall distribution, it was concluded to be due to the greater precipitation of manganese and iron in the drier southern half of the country, and the greater amount of leaching and elutriation of these elements in the wetter conditions in the north. The other elements were not affected by this regional variation (see section 5.3.2(v)).

(vi) R-mode factor analysis of the provincial data

In the previous two sections (iv, v) it has been concluded that variations in background levels of the minor-element content of drainage sediment can be related to differing lithologies or secondary environmental features. These relationships demonstrate the necessity of eliminating the possibility that minor-element background variations are due to either of these features prior to suggesting that areas of high element background delineate metallogenic provinces. It was impossible to interpret most of the bedrock types from single element distributions.

R-mode factor analysis of the provincial data was used as a means to indicate the overall element affinities from which it might be possible to interpret the lithologies and/or secondary features controlling their variation.

The results of the factor analysis indicated three principal associations of minor-elements which could be related to three main lithologies, and one association which could be related to the secondary environment as follows:

(a) a Co-Ni-Cr association was related to basic rocks,

(b) a Pb-Ga association was related to granitic rocks,

(c) a Ti-Cr-V-Ga-Fe_2O_3 association was related to argillaceous schists,

(d) a Mn-Fe_2O_3-V association was related to the secondary environment.

The high R-score patterns of the first three associations delineated, correctly, the broad-scale occurrences of the lithologies to which they had been related. They also indicated the presence of rock types where they had not previously been suspected. For example, the high Co-Ni-Cr R-scores in the northern part of the field area suggest that basic rocks are more prevalent than is suggested on the current geologic maps. It has not been possible to verify this suggestion because of lack of outcrop (see section 5.2.3(i)).
The Mn-Fe_2O_3-V association R-scores corresponded to the single element distributions of manganese and ferric iron, and were generally high in the south and low in the north. Rock and soil sample data indicated that this group of elements were also high over basic and carbonate rocks. It was concluded that the association of these elements reflected their general affinity in basic rocks. In addition, in soils and drainage sediments their actual levels were increased by the concentration of their insoluble hydroxides which

form in two environments as follows: (a) in the high pH conditions over carbonate and basic rocks, and (b) in the drier southern half of the field area (see section 5.3.2.(v)).

The combination of related elements into single groups measured by one variable has made the multi-element data more meaningful and possible to interpret in terms of the primary and secondary features controlling their variations.

Four other factor associations were extracted from the provincial data. They were essentially single element factors and the distribution of their R-scores revealed essentially the same patterns as the moving average results as follows:

(a) The Cu-Ga association was related to the copper metallogenic provinces. It was concluded from rock and soil results that the association of gallium with copper did not have any great geological or secondary significance (see section 5.3.2(iv)).

(b) The strontium association R-scores were high over both the carbonatites near Feira and a belt of carbonate rocks near Mazabuka. This latter feature had not been shown by the moving average strontium values because the differences had been smoothed out over this relatively narrow belt of rocks (see section 5.2.3(v)).

(c) The tin and zinc R-scores revealed essentially the same as the moving-average patterns only in more detail (see sections 5.2.3(v) (vi)). The definition of these single element factors is partly due to their truncated distributions since the majority of the tin, strontium and many zinc samples were below the detection limit.

(vii) Potential of provincial geochemical drainage sediment reconnaissance

Since it was first shown that the background variations of the minor-elements in drainage sediment reflected metallogenic provinces (Webb et al, 1964), the viability and usefulness of broad scale geochemical sampling has now been established in three separate studies: firstly in Sierra Leone (Garrett, 1966), in Uganda (Reedman and Gould, 1970), and in this study over central Zambia.

Broad scale drainage sediment sampling will be most useful in large areas (over 10,000 sq. mi.) where little is known of the distribution of the lithologies or mineralisation. The multi-element data from such a survey can be used firstly for delineating possible metallogenic provinces where more detailed mineral exploration should be carried out, and secondly as means of outlining the distribution of the main lithologies. The sampling density need only be controlled by:

(a) the size of possible target area such as the metallogenic districts and geologic units to be defined,

(b) the accuracy with which geologic boundaries are to be located,

(c) the physical limitations such as drainage density and accessibility, and

(d) the resources made available to the survey.

Drainage sediment was found to be a better sampling medium than soils or rocks for obtaining a broad scale picture of the primary minor-element distribution in conditions such as occur in Zambia.

The minor-elements in soils have undergone a greater differentiation and elutriation than in the drainage sediment. This is indicated by the fact that the minor-element associations extracted from the drainage sediment data by R-mode factor analysis correspond more closely with those extracted from the rock sample data, than do those obtained from the soil data (see Tables 18, 24, 32).

Although ideally fresh rock samples would be a better media for an evaluation of the primary geochemistry than drainage sediment, the collection and analysis of a sufficiently large number of samples to be representative would be extremely difficult and prohibitively expensive even in areas of good outcrop, particularly where the lithology is heterogeneous. In areas of poor outcrop such as occur on the plateau of central Zambia, it is impossible.

8.1.2 R-mode factor analysis of regional reconnaissance drainage sediment multi-element data

R-mode factor analysis was applied to the multi-element regional reconnaissance data from Kadola and Lusaka East to evaluate it as a method of obtaining an improved interpretation in terms of the bedrock geology, mineralisation and secondary environment.

(i) R-mode factor analysis of Kadola data

The minor-element associations indicated by R-mode factor analysis of the Kadola drainage sediment data correctly reflected the presence of three main bedrock types. The high R-scores of these associations also correctly delineated the areas of occurrence of these bedrock types as follows.

(a) A Cu-Ni-Cr-Co association indicated the presence of basic rocks not previously known to occur in Kadola. The R-score distribution showed that they were associated with an area of Muva quartzites. The dominant copper loading in the association suggested the presence of copper mineralisation with the basic rocks. This interpretation was subsequently proved correct by diamond drilling which located talc and hornblende schists interbedded with quartzites with minor mineralisation (see section 6.2.5(iv)).

(b) A Ti-V-Cr-Ni-Ga-Co association was found to reflect argillaceous schists. High Ti-V-Cr-Ni-Ga-Co R-scores indicated an area mapped as limestone to be underlain by argillaceous schists. Subsequent pitting, soil sampling and photo interpretation showed this indication was in fact correct. High R-scores in this association also indicated facies of limestone which included ilmenite as an accessory mineral (see section 6.2.5(i)).

(c) A Pb-Ga association was found to reflect acid crystalline units in the field area (see section 6.2.5(ii)).

(d) A Mn-Fe_2O_3 association was found to reflect carbonate and basic rocks and the secondary conditions which overly them (see section 6.2.5(iii)).

These interpretations of the multi-element regional geochemical data at the same time as compiling a geologic map from photo interpretation and limited field mapping would have been extremely useful. Although no mineralisation factor is likely to be extracted because they would not form an overall correlation-coefficient an interpretation of the single element data maps in conjunction with R-score would have greatly aided the search for possible mineralisation. For example, a combination of high level values over an area with high Ti-Cr-V-Ni-Ga-Co and/or Mn-Fe_2O_3 association R-scores would have indicated possible lead mineralisation in the vicinity of schists and/ or carbonate rocks, such as occurs at Millberg (see section 6.2.5(ii)).

R-mode factor analysis from rock and soil sample data proved these relationships correct. In addition, the data from the drainage sediment was shown to give a more representative picture of the primary geochemistry than the soils. This was illustrated by the minor-element associations extracted from the drainage sediment data corresponding more closely with those from the rock sample data, than do those obtained from the soil data (see section 6.2.5).

(ii) R-mode factor analysis of Lusaka East data

The minor-element associations indicated by the R-mode factor analysis of the Lusaka East drainage sediment data correctly reflected the presence of the same rock types as in Kadola. The high R-scores of these associations delineated, for the most part, correctly the areas of occurrence of these rock types as follows:

(a) A Ni-Cr-Co-Cu-V-Fe_2O_3 association reflected the presence of basic rocks. High R-scores of this association correctly defined the mapped units of basic rock, and also indicated an extensive area mapped as granite gneiss which soil sampling indicated as being underlain by basic rock (see section 6.3.3(i)).

(b) A Pb-Ga association reflected the presence of granites. High Pb-Ga R-scores defined correctly the areas of granite and granite gneiss (see section 6.3.3(ii)).

(c) A Ti-Ga-Cr-Cu-V association reflected the presence of mica schist units. High R-scores of this association defined the areas where schist and basic rocks occurred. Areas of basic rock could be differentiated from areas of schist by having, in addition, high Ni-Cr-Co-Cu-V-Fe_2O_3 association R-scores (see section 6.3.3(iv)).

(d) A Mn-Fe_2O_3-Co-V association was found to reflect sediments drained from basic rocks and sandy stream sediments as opposed to clayey dambo drainage sediments. The high R-scores of this association were, therefore, over basic rocks and in the escarpment areas (see section 6.3.3(iii)).

R-mode factor analysis from rock and soil data confirmed these relationships. In addition, they confirmed that data from the drainage sediment gave a more representative picture of the primary geochemistry than did the soils, in the same way as the factor analysis results from both the Kadola and provincial data (see Table 32).

(iii) Factor associations reflecting minerals

Minor element associations extracted by R-mode factor analysis from Lusaka East rock samples were shown to be more easily interpreted in terms of specific minerals rather than the more general rock classification (see section 6.4). This overcame the problem where a sample had high R-scores in more than one association since the combination of high R-scores of particular associations, which represented particular minerals, led to a classification of each sample as a particular rock type which included those minerals.

This classification was not attempted on drainage sediment data. But minor-element associations from the drainage sediment data were very similar to those extracted from the rock data. If this method of interpretation could be used on drainage reconnaissance data it would greatly simplify the evaluation of the factor results since only one map would have to be used. The derivation of each sample having been allocated to a particular rock type.

(iv) General conclusions and potential value of R-mode factor analysis of geochemical drainage sediment data

The results of R-mode factor analysis of the data from three areas indicates that the technique can identify the main element affinities.

Under most circumstances, providing elements characteristic of the various lithologies and other controlling features are included, these element associations can be related to the main primary and secondary features. The distribution of the R-scores of each association defined the primary and secondary features which the minor-element groupings reflect. In certain instances they indicated the presence of rock types where they were not previously known to exist.

The overall minor-element affinities indicated from Kadola, Lusaka East and the provincial central Zambia drainage sediment data by R-mode factor analysis were in fact very similar, and the lithologies which they reflected were shown in each case to be as follows:

(a) an association dominated by titanium and including chromium, vanadium and gallium was shown to reflect schists and argillaceous rocks,

(b) an association dominated by lead and including gallium was shown to reflect granites and granite gneisses,

(c) an association which included nickel, chromium and cobalt was shown to reflect basic rocks,

(d) an association dominated by manganese and including ferric iron was shown to reflect the secondary environment. In so far as the secondary environment was controlled by carbonate and basic rocks this association reflected these rock types also. This was particularly true in Kadola. In Lusaka East the manganese and ferric iron association was also a reflection of sample type and in the provincial area of the rainfall distribution.

Despite this apparent stability of the minor-element associations indicated above which are extracted from the various sets of data, it was pointed out in section 7.3.2 that the identification of a particular association is dependent on the overall linear correlation coefficient between each pair of variables. The overall correlation coefficients will in turn be dependent on:

(a) the controlling features, for example lithology, which have been sampled and their presence measured by the analyses of a particular variable,

(b) the proportion of samples derived from each controlling feature,

(c) the relative disposition of the data clusters between each pair of variables due to the various controlling features which have been sampled. The differences in element level due to the different controlling features is embodied in this last aspect.

Under most conditions the overall element associations will probably reflect some of the main controlling features, as has been shown in the above examples. It cannot be concluded, however, that because an association is indicated by R-mode factor analysis that it necessarily reflects a controlling feature.

It is important, therefore, that the minor-element associations extracted by R-mode factor analysis are not interpreted with too great a rigidity, so that geochemically nonsensical associations are considered.

As a multi-variate technique R-mode factor analysis will remain a useful technique of interpreting multi-element geochemical data: (a) when there are a large number of samples, and (b) when an interpretation of the main element affinities is required.

8.1.3 Analytical methods used for provincial and regional geochemical reconnaissance

The rapid methods of analysis used in this study proved generally to be adequate for the purposes for which they were used, but measurements of accuracy and statistical handling of the data established that it was important to monitor the accuracy and to increase the sensitivity as far as possible.

(i) Accuracy

Variations of different element levels between the different analytical methods and with time by the same method indicated how important it is to monitor these changes when large groups of data have to be analysed and their results compared (see section 4.4.5).

(ii) Sensitivity

It is important to have data with continuous distributions if parametric statistics are to be used. Truncated distributions with a large percentage of samples below and above the lower and upper detection limits, respectively, greatly reduces the statistical value of the data. If an interpretation of geochemical data is to be made within its background range of values then its sensitivity within that range must be adequate and its precision within that range of values must also be measured and be as high as possible.

(iii) Measurement of precision

The measurement of analytical precision by duplicate analysis of a random number of samples was found to be comparable to those from a statistical series control samples, and offered certain advantages over statistical control samples as follows:

(a) the precision measurements are carried out on the same samples as those analysed,

(b) a random selection of samples will give a fair range of the actual element values, and will encounter the main sample matrices present. No previous knowledge of these aspects will be necessary,

(c) a precision measurement can be made for all the elements being measured,

(d) little sample preparation is necessary,

(e) the calculation is simple.

It is admitted that statistical control samples are important for monitoring the element levels between batches of analyses (see section 4.4.6).

8.2 FUTURE WORK

8.2.1 Provincial geochemical reconnaissance

Since the viability of broad scale provincial geochemical reconnaissance was first suggested (Webb et al, 1964) its use has been proved in three separate studies (Garrett, 1966; Reedman and Gould, 1970; and the present study).

It is suggested that provincial geochemical reconnaissance be carried out over an area where relatively little is known of the geologic mapping and limiting target areas for more detailed mineral exploration by regional geochemical reconnaissance. The sampling density of such a programme need only be controlled by the points raised in section 8.1.1(iv).

It is suggested that a helicopter be used for the survey if at all possible, firstly in order to reduce sampling time, and secondly in order to obtain as even a sample density as possible so that samples are more representative and the results easier to analyse statistically.

It is important that samples are analysed for elements which help to distinguish the rock types from which they are derived so that the element variations due to the geology and secondary environment can be interpreted prior to delineating possible metallogenic areas for detailed mineral exploration. The sensitivity should, where possible, be increased for many of the elements currently analysed for mineral exploration purposes so that there is a fair range of values within the background levels.

8.2.2 Recognition of carbonatites and other metallogenic provinces or districts by provincial drainage sediment reconnaissance

Considerable exploration work for carbonatites is being carried out in India and Africa because of their mineral potential, and as a source of phosphate fertiliser. It is considered that the initial exploration stages for the location of the carbonatites would be greatly reduced in time and cost by using provincial reconnaissance methods. As strontium has already been shown to indicate carbonatites from provincial geochemical reconnaissance, it is suggested that research be carried out to determine which of the elements suggested by Deans and Powell (1968) would best differentiate between sedimentary calcareous rocks and carbonatites from drainage sediment samples.

This study has indicated that provincial geochemical reconnaissance can delineate copper and tin metallogenic provinces. It is considered that provinces of other metallogenic areas could also be detected in the same way. It is suggested that provincial reconnaissance methods should be carried out over metallogenic provinces or districts other than those of copper and tin in order to determine whether or not the technique will delineate their boundaries.

8.2.3 Moving average threshold

Moving average analysis used in this study has been shown to be a useful technique for smoothing provincial geochemical data. The resultant map can be thought of as indicating variations in background trends over an area. By plotting the two standard deviation level instead of the average of each search area a 'moving-threshold' map would be formed over a large area. Such a map could be used to determine anomalous samples in subsequent regional reconnaissance surveys within the provincial area. If this method of determining a threshold level is used, however, analytical accuracy between the analyses of the provincial and regional and reconnaissance must be maintained.

8.2.4 Factor analysis

(a) The relationship of minor-element associations in terms of controlling features is not always self evident from the elements used in this study. If some of the major elements typical of the main rock types or other minor-elements specifically occurring in one particular rock type were analysed, the interpretation of the minor-element associations might be greatly facilitated.

(b) Detailed tracing of geological boundaries in areas of deep overburden such as occur in central Zambia by pitting is extremely tedious and difficult and sometimes impossible where there is a high water table. The multi-element analysis of grid soil samples and appropriate multi-variate computerised technique would greatly aid such mapping. Q-mode cluster analysis might be the more appropriate method than R-mode factor analysis if there are fewer than 200 samples. Care would have to be taken, firstly that the soils are residual and secondly that elutriation of the elements determined is not so great that differences cannot be detected. Sensitivity of the analytical method might have to be increased in order to overcome this problem.

(c) One of the disadvantages of R-mode factor analysis is that, although there is data reduction from the number of variates to the smaller number of factors, there is still more than one map to be interpreted. It was shown in section 6.4 that element associations extracted by R-mode factor analysis could be related to minerals, and that an arbitrary level of R-score value indicated the presence of a mineral defined by the appropriate association. The rock type from which the sample was derived could then be classified by the minerals which the R-score indicate to be present.

The recognition of the presence of certain minerals and the classification of the sample as being derived from a particular rock type could be computerised. A single map could then be produced showing the rock types from which each sample was derived.

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APPENDIX I

```
C     AUTHOR
C     A.ARMOUR-BROWN.APPLIED GEOCHEMISTRY,IMPERIAL COLLEGE.
C     LANGUAGE,COMPUTER ,DATE.
C     FORTRAN-IV,IMPERIAL COLLEGE IBM 7094,MARCH 69.
C     PURPOSE-
C     CALCUTES PRECISION FROM DUPLICATES ANALYSES
C     LIMITATIONS-
C     MAXIMUM NUMBER OF DUPLICATES100 BY 13 VARIABLES.N.B.
C     THIS ARRAY SIZE CUOLD BE CHANGED TO OTHER DIMENSIONS.
C     ANY NUMBER OF DUPLICATE SETS CAN BE PROCESSED.
C     SOFTWARE-
C     PUFFT,OR IBJOB,FIOCS.
C     INPUT OF DATA-
C     FIRST DATA CARD IS TITLE CARD-
C     COL 1,MUST HAVE 1 TO INITIATE PROGRAM.COLS 2-79ALPHANUMERIC TITLE
C     2ND.DATA CARD -READS NUMEL=NUMBER OF ELEMENTS,NX=NUMBEROF SAMPLES.
C     LOGOPT=1 INITIATES LOGOPTION
CFORMAT 3I5
C     3RD DATA CARD-READS ELNAM(J)=ELEMENT NAMES.FORMAT 13A6.
C     4TH DATACARD-IFMT=VARIABLE FORMAT IN COLUMNS 1-78.
C     DATA  IN IFMT WITH ONE SAMPLE CONSECUTAVELY BEHIND ITS DUPLICATE.
C     A NEW SET OF DUPLICATES HAS SIMILAR SET OF HEADING CARDS-
C     EACH NEW SET OF DUPLICATES IS STARTED OFF WITH A NEW TITLE CARD
C     WITH 1 IN THE FIRST COLUMN.
C     LAST CARD-AFTER THE LAST SET OF DATA A LAST CARD SHOULD BE PUT AT
C     THE END WITH A BLANK OR ANY INTERGER OTHER THAN 1 IN COLUMN 1 WITH
C     ANY TITLE INFORMATION THAT IS REQUIRED.
C
C      OUTPUT RESULTS-
C     TITLE
C      ELEMENT.=VARIABLE NAME.
C     PERCNT AV DEV.=PERCENTAGE AVERAGE DIFFERENCE OF VARIABLE VAUES
C     BETWEEN DUPLICATES.
C     STD OF DEV.=STANDARD DEVIATIONS OF DIFFERENCES.
C     PERCNT PREC AT 95PERCNT CONF=PRECISION AT THE 95 PERCENT CONFIDENCE
C     LEVEL
C     MIN AND MAX RANGE.=LOWEST AND HIGHEST VALUE OF VARIABLE.
      DIMENSION ELNAM(13),DEV(13),DEV2(13),SDEV(13),SDEV2(13),X(200,13)
      DIMENSIONIFMT(13),XMIN(13),XMAX(13)
      DIMENSION ITITLE(13)
C    READ TITLE.
 1000 READ(5,12)ISTART,(ITITLE(L),L=1,13)
   12 FORMAT(I1,13A6)
      IF(ISTART.NE.1)GO TO 2000
C    READ NUMBER OF ELEMENTS,AND NUMBER OF SAMPLES,LOGOPTION
      READ(5,11)NUMEL,NX,LOGOPT
C    READ ELEMENT NAMES.
      READ(5,10)(ELNAM(J),J=1,NUMEL)
C    READ VARIABLE FORMAT.
      READ(5,10)(IFMT(I),I=1,13)
   10 FORMAT (13A6)
   11 FORMAT (3I5)
C    WRITE TITLE.
      WRITE(6,21)(ITITLE(L),L=1,13)
   21 FORMAT(1H1,13A6,/,1H0,101HELEMENT. PERCNT AV DEV. STD OF DEV. PERC
     1NT PREC AT 95PERCNT CONF. MIN AND MAX RANGE.                     )
C    INITIALISING VARIABLES
      DO 300 J=1,NUMEL
      DEV(J)=0.0
```

```
      DEV2(J)=0.0
      SDEV(J)=0.0
      SDEV2(J)=0.0
      XMIN(J)=100000.0
      XMAX(J)=.00001
  300 CONTINUE
C     DO LOOP READING DUPLICATES.
      DO 110 I=1,NX,2
      READ(5,IFMT)(X(I,J),J=1,NUMEL)
      READ(5,IFMT)(X(I+1,J),J=1,NUMEL)
C     DO LOOP TREATING EACH ELEMENT.
      DO 100 J=1,NUMEL
      IF(LOGOPT.NE.1) GO TO 400
      X(I,J)=ALOG10(X(I,J))
      X(I+1,J)=ALOG10(X(I+1,J))
C     FINDING MAX AND MIN. VALUE.
  400 IF(X(I,J).LT.XMIN(J))XMIN(J)=X(I,J)
      IF(X(I+1,J).LT.XMIN(J)) XMIN(J)=X(I+1,J)
      IF(X(I,J).GT.XMAX(J))XMAX(J)=X(I,J)
      IF(X(I+1,J).GT.XMAX(J)) XMAX(J)=X(I+1,J)
C     CALCULATING DIFFERENCSE BETWEEN DUPLICATE VALUES AND THEIR SQUARES
C     AND SUMMING THEM.
      DEV(J)=(X(I,J)-X(I+1,J))/(X(I,J)+X(I+1,J))
      DEV2(J)=DEV(J)*DEV(J)
C     IF DIFFERENCE IS NEGATIVE TAKE ABSOLUTE VALUE.
      SDEV(J)=SDEV(J)+ABS(DEV(J))
      SDEV2(J)=SDEV2(J)+DEV2(J)
  100 CONTINUE
  110 CONTINUE
C     RN=NUMBER OF DUPLICATES WHICH IS EQUAL TO HALF NUMBER OF CARDS=NX.
      RN=NX/2
C     DO-LOOP TO
C     CALCULATE PARAMETERS AND PRECISION.
      DO200 J=1,NUMEL
      STD=(RN*SDEV2(J)-SDEV(J)*SDEV(J))**0.5/RN
      AVDEV=(SDEV(J)/(RN-1.0))*100.0
      PREC=(STD*200.0)+AVDEV+0.05
      ELNM=ELNAM(J)
      XMN=XMIN(J)
      XMX=XMAX(J)
      IF(LOGOPT.NE.1)GO TO 500
      XMN=10.0**XMN
      XMX=10.0**XMX
C     WRITE ANSWERS.
  500 WRITE(6,20)ELNM,AVDEV,STD,PREC,XMN,XMX
   20 FORMAT(1H0,A6,3X,F7.2,8X,F10.4,6X,F6.1,15X,F10.4,4H TO ,F13.4)
  200 CONTINUE
      N=RN
C     WRITE OUT NUMBER OF DUPLICATES.
      WRITE(6,23) N
   23 FORMAT(1H0,25HNUMBER OF DUPLICATES IS  -  ,I4)
      GO TO 1000
C     WRITE OUT LAST TITLE .
 2000 WRITE(6,22)(ITITLE(L),L=1,13)
   22 FORMAT(1H1,13A6)
      STOP
      END
```

EXAMPLE OF OUTPUT

```
ANAL.PREC.FROM DUPL.ANL.OF CE SPEC AND AT.ABS.DATA OF KADOLA SOIL SAMPLES.

ELEMENT. PERCNT AV DEV. STD OF DEV. PERCNT PREC AT 95PERCNT CONF. MIN AND MAX RANGE.

    PB      4.3           0.099           19.8                      4.00 TO    60.00

    GA     17.5           0.204           40.9                      8.00 TO    80.00

    V      19.4           0.149           29.9                      5.00 TO   800.00

    CU     11.7           0.147           29.4                     10.00 TO   290.00

    ZN      7.1           0.088           17.7                     10.00 TO    80.00

    TI      9.2           0.104           20.8                   3000.00 TO 22000.00

    NI     14.9           0.123           24.7                     10.00 TO   290.00

    CO     13.1           0.115           23.1                     10.00 TO   100.00

    MN     25.5           0.214           42.8                      4.00 TO   900.00

    CR     10.9           0.148           29.7                     40.00 TO  1000.00

NUMBER OF DUPLICATES IS  -    79
```

ALACRA HI-SPEED 11x15 5/16

APPENDIX 2

Pit Profiles in Kadola

PIT 1*

Depth	Colour of Grain Size	Composition and Remarks
0 - 3"	Grey silty sand	Quartz and little organic material
3"-6"	Yellowish rusty silty sand	Quartz silt
6"-2'	Yellowish rusty silty clayey sand	Quartz clay silt
2'-4'	Grey and red mottled	Quartz clay silt laterite pellets, and quartz pebbles
4'-10'	Grey and red mottled	Quartz clay silt laterite pellets, and quartz pebbles Laterite pellets tending to form aglomerations and massive laterite
10'-15'	Grey and red mottled silty clay with weathered rock fragments	Clay silt weathered slickensided phyllite foliation about 280/65°S.

---

*For location of pits see figure 43

PIT 2

Depth	Colour and Grain Size	Composition and Remarks
0 - 3"	Grey silty fine sand	Quartz silt little organic material
3"-6"	Yellowish rusty silty fine sand	Quartz silt
6"-2'	Darker yellow rusty than above, silty clayey fine sand	Quartz, silt, clay
2'-3'	Reddish rusty silty clayey fine sand	Quartz laterite pellets silt and clay
3'-9'	Reddish rusty	Massive laterite
9'-11'	Red and grey mottled silty clay	Clay silt weathered phyllite foliation 290/80°S.

PIT 3

0 - 3"	Grey silty fine sand	Quartz silt little organic material
3"-6"	Yellowish grey silty fine sand	Quartz silt
6"-2'3"	Yellowish rusty. Silty clayey fine sand	Quartz silt clay
2'3"-6'	Reddish rusty	Massive laterite
6'-10'	Reddish rusty	Massive laterite with quartz pebbles
10'	Water table	

PIT 4

Depth	Colour and Grain Size	Composition and Remarks
0 - 3'	Dark red silty clay	Clay silt
3'-6'	Red and white silty clay	Clay silt
6'-20'	White clay	Mylonised clay
20'-28'	White and light green along fracture surfaces	Clay and talc schist Slickensided plane 130/70°NE.

APPENDIX 3

Drill Hole Logs

Drill hole KP46*

0 - 10'	Soil
10'- 29'	Quartzite and schist fragments, partially laterised.
29'- 75'	Schist and sericite, weathered.
75'- 92'	Chlorite and talc schist.
92'-220'	Talc schist with magnesite porphyroblasts.
220'-238'	Chlorite schist.
238'-324'	Sericite schist with biotite blebs.
324'-381'	Chlorite, biotite schist with garnet porphyroblasts.

Drill hole KP48

0 - 20'	Soil
20' -112'	Weathered talc schist.
112'-150'	Talc schist with carbonate inclusions.
150'-213'	Quartzite with pyrite in fractures at 171 feet.
213'-226'	Quartz-sericite schist with garnet porphyroblasts, disseminated pyrite between 223'-226'.
226'-268'	Schist and quartzite with magnetite.

Drill hole KP49

0 - 15'	Soil
15' - 53'	Decomposed sericite schist.
53' -107'	Weathered chlorite schist.
107'-155'	Talc schist with magnetite porphyroblasts, partially weathered.
155'-164'	Sericite schist with biotite blebs.
164'-218'	Massive quartzite, with occasional chalcocite and chalcopyrite mineralisation.
218'-351'	Quartzite, sericite and chlorite schist and biotite schist in places with garnet porphyroblasts and magnetite.

*For location of drill holes see Fig. 46

Drill hole KP51

0 - 15'	Soil with laterite.
15'-24'	Laterised schist.
24'-50'	Decomposed sericite schist.
50'-58'	Talc, sericite schist with wad and limonite weathering.
58'-72'	Talc, sericite, chloritic schist, weathered.
72'-150'	Talc, chloritic schist with magnesite porphyroblasts.

APPENDIX 4

List of Factor R-Scores of Rock Samples from Lusaka East Extracting 6 Factors from 11 Variables (165 samples)

Sample No.	Factor Associations	R-Scores Ni-Cr-Fe Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe	Mineral content and/or rock type Determined from R-scores	Determined from hand specimen
9500		-0.64	-1.80	-1.25	-0.30	-0.67	0.25	Quartzite	Quartzite
9501		-0.96	-2.17	-1.18	-0.00	-0.25	-0.85	Quartzite	Quartzite
9502		-0.21	-0.75	-0.47	-1.19	1.61	0.01	Muscovite schist	Muscovite schist
9503		0.43	-1.13	1.72	-0.61	1.08	1.17	Muscovite, biotite schist with iron minerals	Biotite, muscovite schist red weathered
9504		-0.01	-1.43	-0.63	-0.55	0.22	-0.33	Quartzite	Quartzite
9505		-0.20	0.11	-0.89	-0.20	1.71	0.66	Muscovite schist with iron minerals	Muscovite schist red weathered
9506		-0.24	-1.83	-1.37	0.19	-1.50	-0.84	Quartzite	Quartzite
9507		-0.44	-1.43	-1.35	0.22	-1.15	-0.91	Quartzite	Quartzite
9508		-0.03	-0.48	-1.04	-2.01	2.27	-1.78	Muscovite schist	Muscovite schist red weathered
9509		-0.02	-1.35	-1.21	-0.25	-1.02	-0.85	Quartzite	Quartzite
9510		-0.34	-2.26	-0.86	-1.54	1.58	-2.00	Muscovite schist	Quartz muscovite schist
9511		0.32	0.06	-0.87	0.39	1.34	-1.57	Muscovite schist	Muscovite schist
9512		-0.33	-1.48	-1.01	-0.69	0.65	-1.52	Muscovite schist	Muscovite schist
9513		-0.14	-1.81	-1.06	-0.50	-0.71	-0.31	Quartzite	Quartzite
9515		-0.47	-0.01	0.20	0.16	-0.34	-0.25	Quartzite	Quartzite
9516		0.54	0.52	-0.40	1.09	2.10	0.80	Epidosite near Cu mineralisation	Talcose schist red weathered near Buffalo Hill copper mineralisation
9517		1.21	0.41	0.00	-0.59	1.23	0.30	Amphibolite, muscovite schist	Talcose, muscovite, quartz schist
9518		1.17	-0.04	0.21	-0.94	1.36	-0.35	Amphibolite, muscovite schist	Talcose, muscovite, quartz schist

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9520	1.52	0.84	0.15	-1.56	-0.06	1.16	Epidote with iron minerals	Talcose schist red weathered
9521	0.43	0.52	-0.81	1.16	1.27	-1.08	Muscovite granite near Cu mineralisation	Quartz muscovite schist near Buffalo Hill Cu mineralisation
9522	0.44	-0.20	-0.45	1.35	1.46	-0.33	Muscovite schist near Cu mineralisation	Quartz muscovite schist near Buffalo Hill Cu mineralisation
9523	0.15	-0.40	-0.92	0.91	0.98	-0.76	Muscovite near Cu mineralisation	phyllite near Buffalo Hill Cu mineralisation
9524	-0.10	-1.01	-1.07	0.60	1.31	0.28	Muscovite near Cu mineralisation	Phyllite near Buffalo Hill Cu mineralisation
9525	-0.22	-0.43	-1.73	0.96	1.44	-0.07	Muscovite near Cu mineralisation	Phyllite near Buffalo Hill Cu mineralisation
9526	0.23	-0.45	-0.45	2.16	1.67	0.71	Muscovite schist with iron minerals near Cu mineralisation	Phyllite purplish red weathered near Buffalo Hill Cu mineralisation
9527	-0.50	-2.23	-0.41	0.23	-0.80	0.12	Quartzite	Quartzite
9528	-0.50	-0.78	-1.69	0.88	0.58	0.21	Muscovite schist near Cu mineralisation	Phyllite near Buffalo Hil Cu mineralisation
9529	0.53	0.00	-1.15	2.62	1.32	-0.17	Amphibolite, muscovite schist near cop	Talcose muscovite schist near Buffalo Hill Cu mineralisation
9530	-0.16	-0.44	-0.76	-1.79	1.35	1.02	Muscovite schist with iron minerals	Muscovite schist red weathered
9531	-0.45	-1.39	-1.11	-1.58	-0.59	-1.20	Quartzite	Quartzite
9532	-0.20	-0.31	1.53	0.61	0.45	0.99	Biotite with iron minerals near Cu mineralisation	Biotite schist, red weathered near Buffalo Hill Cu mineralisation
9533	-0.78	-0.07	-0.58	-1.05	-0.11	0.08	Quartzite	Quartzite
9534	-0.99	0.72	2.39	0.25	-0.46	-0.27	Biotite granite	Biotite, quartz, muscovit schist

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9535	0.50	-0.10	0.40	0.48	1.40	0.37	Amphibolite, muscovite near Cu mineralisation	Talcose phyllite near Buffalo Hill Cu mineralisation
9536	-0.44	0.04	0.23	-1.33	0.19	0.28	Quartzite	Quartzite
9537	-1.12	-2.03	-1.18	-1.42	-0.22	-0.48	Quartzite	Quartzite
9538	0.05	-1.39	-1.16	0.03	-1.59	0.26	Quartzite	Quartzite
9539	-0.19	-1.04	0.42	-1.88	0.65	0.28	Muscovite schist	Muscovite schist
9540	0.28	0.27	0.14	0.36	-0.06	0.99	Quartzite with iron minerals	Quartz muscovite schist with garnet porphyroblasts
9541	-0.40	0.38	1.84	0.52	0.61	-1.60	Biotite muscovite schist near Cu mineralisation	Quartz, muscovite, biotite schist; no known mineralisation
9542	-0.66	-1.73	-1.26	0.13	-1.02	-1.19	Quartzite	Quartzite
9543	-0.72	-1.86	-1.20	0.14	-0.91	-1.21	Quartzite	Quartzite
9544	-0.78	-1.92	-1.32	0.19	-0.93	-1.12	Quartzite	Quartzite
9545	-0.66	0.16	-0.11	1.23	1.28	-0.76	Muscovite schist near Cu mineralisation	Muscovite schist; no known Cu mineralisation
9546	-0.10	-1.37	-0.26	-0.44	0.31	-1.47	Quartzite	Quartzite
9547	-1.83	-0.27	0.94	0.27	1.44	-1.06	Biotite, muscovite schist	Quartz, biotite, muscovite schist
9548	-1.00	0.03	-0.53	-1.26	-0.97	-0.48	Quartzite	Quartzite
9549	-1.58	0.52	-0.03	-1.19	-0.59	-0.99	Granite	Granite
9550	-0.39	-0.44	0.38	-0.84	1.58	0.28	Muscovite schist	Quartz, muscovite schist
9551	-0.19	0.19	0.22	0.56	0.97	-0.02	Muscovite schist near Cu mineralisation	Quartz, biotite, muscovite schist; no known mineralisation
9552	0.54	-0.15	-0.60	0.93	1.37	-0.25	Amphibolite, muscovite schist near Cu mineralisation	Talcose quartz muscovite schist; no known mineralisation
9553	1.66	1.45	-0.79	-1.90	-0.50	-0.88	Amphibole granite	Amphibole, biotite, quartzite in granite gneiss

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9554	-0.23	0.75	-0.96	-1.22	0.41	-0.23	Granite	Muscovite schist in granite gneiss
9555	0.30	0.16	-1.18	0.90	2.02	2.07	Muscovite schist with iron minerals; near Cu mineralisation	Muscovite schist red weathered; no known mineralisation
9556	-0.05	-0.19	0.34	-0.68	1.34	-0.03	Muscovite schist	Quartz, muscovite schist
9557	-0.48	0.86	-0.21	-0.70	0.19	-0.86	Granite	Granite
9558	-0.76	0.55	-0.37	-0.69	-0.78	-0.17	Granite	Granite
9559	-2.01	0.84	-1.31	-1.20	-0.80	0.24	Granite	Quartzite in granite gneiss
9560	-1.05	0.61	-0.95	-1.32	-0.13	-1.18	Granite	Quartzite in granite gneiss
9561	-0.95	0.46	-1.06	-1.09	-0.18	-1.27	Granite	Quartzite in granite gneiss
9562	-1.32	1.41	0.10	0.12	-0.19	-1.14	Granite	Granite
9563	-0.87	-1.53	-1.38	-0.62	-1.12	-0.93	Quartzite	Quartzite
9564	0.23	-0.52	-1.34	0.43	-2.87	0.19	Quartzite	Quartzite
9565	-1.45	0.61	-0.13	-0.54	-0.67	1.05	Granite with iron minerals	Muscovite, biotite, quartzite in granite gneiss
9566	-1.17	0.63	0.97	-0.45	0.26	-0.14	Biotite granite	Biotite granite
9567	-1.12	0.96	1.00	-0.47	-0.18	-0.23	Biotite granite	Biotite granite
9569	-1.38	1.33	-0.04	-0.63	-0.02	-0.09	Granite	Granite
9570	-1.33	-1.62	0.14	-0.64	-0.93	0.50	Quartzite with iron minerals	Quartzite, red weathered
9571	-0.48	-1.23	-1.10	0.18	-2.21	-0.82	Quartzite	Quartzite
9572	-1.40	1.40	-0.84	-0.73	-2.33	0.24	Granite	Granite
9573	-1.16	1.61	-1.46	-0.29	-2.10	-0.28	Granite	Granite
9574	-1.77	0.75	-0.43	0.12	-0.88	-0.30	Granite	Granite
9575	-1.50	1.58	-1.48	-0.53	-1.80	-0.24	Granite	Granite
9576	-1.05	0.93	-0.51	-0.67	-1.64	-0.11	Granite	Granite
9577	0.64	0.13	0.75	-0.85	0.18	0.23	Amphibolite, biotite schist	Quartz, biotite schist
9578	-0.49	0.14	0.39	-0.86	0.17	-0.09	Quartzite	Quartz, feldspar, muscovite schist

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9579	-1.33	0.58	0.62	-0.82	-0.04	0.11	Biotite granite	Biotite granite
9580	-1.90	1.05	1.98	-2.11	-0.63	-0.62	Biotite granite	Biotite granite
9581	-1.58	0.10	0.57	-0.85	-0.72	-0.13	Biotite schist	Quartz, feldspar, amphibolite schist
9582	-0.95	0.72	-0.29	-0.60	-0.03	0.10	Granite	Granite
9583	-1.99	0.68	-0.34	-0.72	0.01	-0.98	Granite	Granite
9584	-1.47	0.59	-0.41	-0.80	-0.28	-1.22	Granite	Granite
9585	-1.67	0.62	-0.61	-1.15	-0.92	-0.71	Granite	Biotite granite
9586	2.14	0.60	-0.83	0.62	0.02	0.83	Epidote, amphibole with iron minerals; near Cu mineralisation	Epidote, amphibole, haematite near Chakwanga mine
9587	-1.09	0.75	0.68	0.51	-0.05	0.27	Biotite granite near Cu mineralisation	Biotite granite near Chakwenga mine
9588	0.59	1.13	-0.55	-0.29	0.56	0.61	Epidote, amphibole with iron minerals	Epidote, magnetite
9589	1.06	1.38	-0.90	-0.06	-0.02	0.71	Epidote, amphibole with iron minerals	Epidote, magnetite
9590	2.35	0.80	-0.10	0.41	-0.41	0.31	Epidote, amphibole with iron minerals	Amphibole, epidote, magnetite
9591	0.80	-0.38	0.40	-0.81	-0.36	-0.06	Amphibolite	Biotite quartzite
9592	0.42	-0.21	1.29	0.09	0.10	0.69	Biotite with iron minerals	Quartz biotite schist
9493	2.33	-0.44	1.44	2.01	-0.25	0.69	Amphibole, biotite with iron minerals near Cu mineralisation	Amphibolite, biotite schist, rusty red weathered near Chakwenga mine
9594	1.37	0.39	1.14	0.52	0.56	1.39	Amphibole, biotite with iron minerals near Cu mineralisation	Amphibolite, biotite schist, rusty red weathered near Chakwenga mine
9595	1.99	0.09	1.03	0.62	0.09	1.68	Amphibole, biotite with iron minerals near Cu mineralisation	Amphibolite, biotite schist, rusty red weathered near Chakwenga mine

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9596	0.42	-0.25	1.02	0.18	1.70	1.37	Biotite muscovite schist with iron minerals	Biotite muscovite schist
9597	1.59	-0.48	0.56	-0.10	0.61	0.98	Amphibolite, biotite muscovite with iron minerals	Amphibolite, biotite, muscovite schist
9598	0.22	0.11	1.68	0.01	-0.47	0.24	Biotite	Biotite, muscovite schist
9599	-0.49	0.20	1.74	-0.74	-0.41	0.00	Biotite schist	Biotite schist
9600	0.86	-0.98	1.19	-0.07	1.05	0.74	Amphibolite, biotite, muscovite schist with iron minerals	Amphibolite, biotite, muscovite schist, red weathered
9601	-0.99	1.17	2.11	-0.07	-0.45	1.00	Biotite granite with iron minerals	Biotite granite, rusty red weathered
9602	-0.86	0.80	0.39	-0.36	-1.16	-0.04	Granite	Granite
9603	-1.33	0.89	0.48	-0.39	-0.04	-1.27	Biotite granite	Amphibole granite
9605	-0.56	1.29	2.78	0.10	-0.85	-0.94	Biotite granite	Amphibole granite
9606	-0.79	1.46	1.21	0.12	-1.07	-0.94	Biotite granite	Biotite granite
9607	-0.56	1.33	1.76	0.33	-0.82	-1.16	Biotite granite	Biotite granite
9608	-0.51	1.05	1.28	0.57	-0.80	-1.36	Biotite granite near Cu mineralisation	Biotite granite, no known mineralisation
9609	-0.33	1.08	2.01	0.64	-0.10	-1.22	Biotite granite near Cu mineralisation	Biotite granite, no known mineralisation
9610	0.86	0.55	-0.31	0.17	-0.82	-1.51	Amphibole granite	Amphibole granite
9611	0.61	0.83	-0.39	0.39	-0.36	-1.54	Amphibole granite	Amphibole granite
9612	0.12	0.84	0.87	0.20	-0.38	-1.57	Biotite granite	Granite
9613	0.44	0.39	0.46	0.12	-0.15	-1.69	Quartzite	Amphibole biotite granite
9614	0.03	1.04	0.12	-0.03	-0.35	-1.46	Granite	Granite
9615	0.36	0.81	-0.68	-0.07	-0.57	-0.66	Granite	Granite
9617	-0.14	0.54	-0.83	0.05	-0.61	-0.40	Granite	Granite
9618	0.39	1.01	0.42	0.23	-0.43	-1.38	Granite	Granite
9619	1.03	0.85	0.65	0.30	0.55	-0.45	Biotite, amphibole, muscovite granite	Talcose, muscovite, biotite, quartz schist
9620	1.72	0.99	0.99	0.24	0.21	0.00	Biotite, amphibole granite	Talcose, biotite schist

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn-Fe		
9621	1.94	0.66	0.52	0.55	-1.59	1.82	Epidote, amphibole, biotite with iron minerals, near Cu mineralisation	Amphibole,muscovite, biotite, quartz schist, near M0160 Cu mineralisation
9622	0.20	-0.14	-0.77	-0.12	-0.45	-1.33	Quartzite	Quartzite
9623	1.86	1.32	-0.03	1.62	-0.55	-0.72	Amphibolite granite near Cu mineralisation	Epidote amphibolite near M0160 Cu mineralisation
9625	-0.22	-1.44	-1.32	0.17	-1.38	-0.88	Quartzite	Quartzite
9626	2.56	0.63	0.06	1.25	-0.21	0.14	Amphibole granite near Cu mineralisation	Talcose, muscovite schist no known mineralisation
9627	0.82	-0.09	0.12	0.06	0.90	0.30	Amphibolite, muscovite schist	Talcose, muscovite schist
9629	0.06	-1.18	-0.34	0.49	-1.85	-0.42	Quartzite near Cu mineralisation	Quartzite near M0160 Cu mineralisation
9630	0.12	2.10	0.11	0.26	-0.06	1.91	Epidote with iron mineral	Epidote with magnetite and/or specular haematite
9631	0.28	0.13	3.30	2.97	0.60	1.90	Biotite, muscovite schist near Cu mineralisation	Talcose, biotite, muscovite schist near M0160 Cu mineralisation
9632	0.34	0.06	-0.24	0.57	0.44	-0.38	Quartzite near copper mineralisation	Quartzite near M0160 Cu mineralisation
9633	-0.75	0.21	-0.44	0.30	1.00	0.06	Muscovite schist	Muscovite schist
9634	1.50	2.17	-0.22	-0.24	-0.29	1.02	Epidote, amphibolite with iron mineralisation	Epidote, magnetite and/or specular haematite
9635	1.53	2.29	-0.06	1.01	-0.43	0.62	Epidote, amphibolite with iron minerals, near Cu mineralisation	Epidote, magnetite; near M0160 Cu mineralisation
9636	3.27	-0.62	1.13	-0.27	-0.59	1.23	Amphibole, biotite with iron minerals	Chloritic biotite schist near M0160 Cu mineralisation

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn Fe		
9637	0.09	0.23	2.07	2.04	0.77	1.48	Biotite, muscovite schist with iron minerals, near Cu mineralisation	Biotite, epidote with haematite near M0160 Cu mineralisation
9638	-0.34	0.19	-0.28	1.07	0.86	-0.04	Muscovite schist near Cu mineralisation	Quartz, muscovite schist near M0160 Cu mineralisation
9639	-0.21	1.04	-0.69	0.33	-0.38	1.34	Granite with iron minerals	Biotite granite with red haematite
9640	-1.10	-1.16	-1.47	-0.37	-1.47	0.18	Quartzite	Quartzite
9641	0.13	1.04	0.18	0.56	-0.34	-0.91	Granite near Cu mineralisation	Muscovite sillimanite schist ; no known mineralisation
9642	-0.01	0.05	-0.27	-1.48	0.60	-0.81	Muscovite schist	Muscovite schist
9643	0.79	-0.03	0.97	-0.69	0.87	0.27	Amphibolite, biotite muscovite schist	Talcose, biotite, muscovite schist
9644	0.27	0.53	0.59	-0.47	0.33	1.30	Epidote with iron minerals	Epidote with magnetite
9645	0.93	-1.61	0.32	-1.87	1.41	0.85	Amphibolite, muscovite with iron minerals	Talcose muscovite schist with rusty red weathered
9646	-0.28	0.67	2.06	0.41	1.25	2.23	Epidote, biotite, muscovite with iron minerals	Epidote, biotite, muscovite schist with haematite.
9647	0.31	1.37	0.10	0.67	0.81	0.57	Epidote, muscovite with iron minerals near Cu mineralisation	Epidote, quartz, haematite, no known mineralisation
9648	1.72	0.24	1.52	2.52	0.62	0.37	Amphibolite, biotite, muscovite schist near Cu mineralisation	Talc biotite schist; no known mineralisation
9649	1.23	0.66	0.68	2.33	0.86	1.43	Epidote, amphibolite, biotite, muscovite, with iron minerals near Cu mineralisation	Talc, muscovite, biotite schist, no known mineralisation

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn Fe		
9637	0.09	0.23	2.07	2.04	0.77	1.48	Biotite, muscovite schist with iron minerals, near Cu mineralisation	Biotite, epidote with haematite near M0160 Cu mineralisation
9638	-0.34	0.19	-0.28	1.07	0.86	-0.04	Muscovite schist near Cu mineralisation	Quartz, muscovite schist near M0160 Cu mineralisation
9639	-0.21	1.04	-0.69	0.33	-0.38	1.34	Granite with iron minerals	Biotite granite with red haematite
9640	-1.10	-1.16	-1.47	-0.37	-1.47	0.18	Quartzite	Quartzite
9641	0.13	1.04	0.18	0.56	-0.34	-0.91	Granite near Cu mineralisation	Muscovite sillimanite schist ; no known mineralisation
9642	-0.01	0.05	-0.27	-1.48	0.60	-0.81	Muscovite schist	Muscovite schist
9643	0.79	-0.03	0.97	-0.69	0.87	0.27	Amphibolite, biotite muscovite schist	Talcose, biotite, muscovite schist
9644	0.27	0.53	0.59	-0.47	0.33	1.30	Epidote with iron minerals	Epidote with magnetite
9645	0.93	-1.61	0.32	-1.87	1.41	0.85	Amphibolite, muscovite with iron minerals	Talcose muscovite schist with rusty red weathered
9646	-0.28	0.67	2.06	0.41	1.25	2.23	Epidote, biotite, muscovite with iron minerals	Epidote, biotite, muscovite schist with haematite.
9647	0.31	1.37	0.10	0.67	0.81	0.57	Epidote, muscovite with iron minerals near Cu mineralisation	Epidote, quartz, haematite, no known mineralisation
9648	1.72	0.24	1.52	2.52	0.62	0.37	Amphibolite, biotite, muscovite schist near Cu mineralisation	Talc biotite schist; no known mineralisation
9649	1.23	0.66	0.68	2.33	0.86	1.43	Epidote, amphibolite, biotite, muscovite, with iron minerals near Cu mineralisation	Talc, muscovite, biotite schist, no known mineralisation

	Ni-Cr-Fe-Mn-Ti	Pb-Ga-Mn	Zn-Ti	Cu	V-Ti-Cr-Ga	Co-V-Mn Fe		
9689	1.48	0.33	0.62	0.51	-0.12	-0.22	Amphibolite, biotite near Cu mineralisation	Biotite granite, no known mineralisation
9697	-0.46	-2.10	0.88	-0.20	1.87	-0.09	Biotite, muscovite schist	Biotite, muscovite schist
9698	-0.85	-2.75	-0.28	0.01	-2.13	2.20	Quartzite with iron minerals	Biotite schist